APPENDIX A
DESIGN CONSIDERATIONS FOR LANDFARMS

1.0 INTRODUCTION

Landfarming is one form of a class of technologies collectively described as bioremediation. In landfarming, microorganisms present in soil are stimulated to use the contaminants (usually hydrocarbons) already present as an energy and/or carbon source. The hydrocarbons are either incorporated into biomass or transformed into simpler molecules, with some of the material mineralized to carbon dioxide and water. Landfarming is almost always performed on surface or shallow soils, typically to depths less than 2 feet.

Bioremediation processes require the application of proper nutrients, pH controllers, mixing and water to promote the maximum microbial degradation of the hydrocarbons present. In addition, the migration of materials of concern from the landfarm area must be controlled to prevent potentially hazardous materials from escaping into and impacting the surrounding area.

The process operates very much like a crop farm, except that the "crop" is composed of microorganisms which are usually capable of using the hydrocarbons as a food source. A flowchart showing the landfarm application strategy is provided in Figure A-l.

Most landfarms treat hydrocarbon fuels and fuel products. In general, the appropriate state agency will require a work plan to include operations and closure procedures prior to the commencement of landfarm operations. Usually, the agency involved is the state environmental regulatory agency, but there are exceptions (e.g., the Texas Railroad Commission has jurisdiction over petroleum exploration and production spills in Texas).

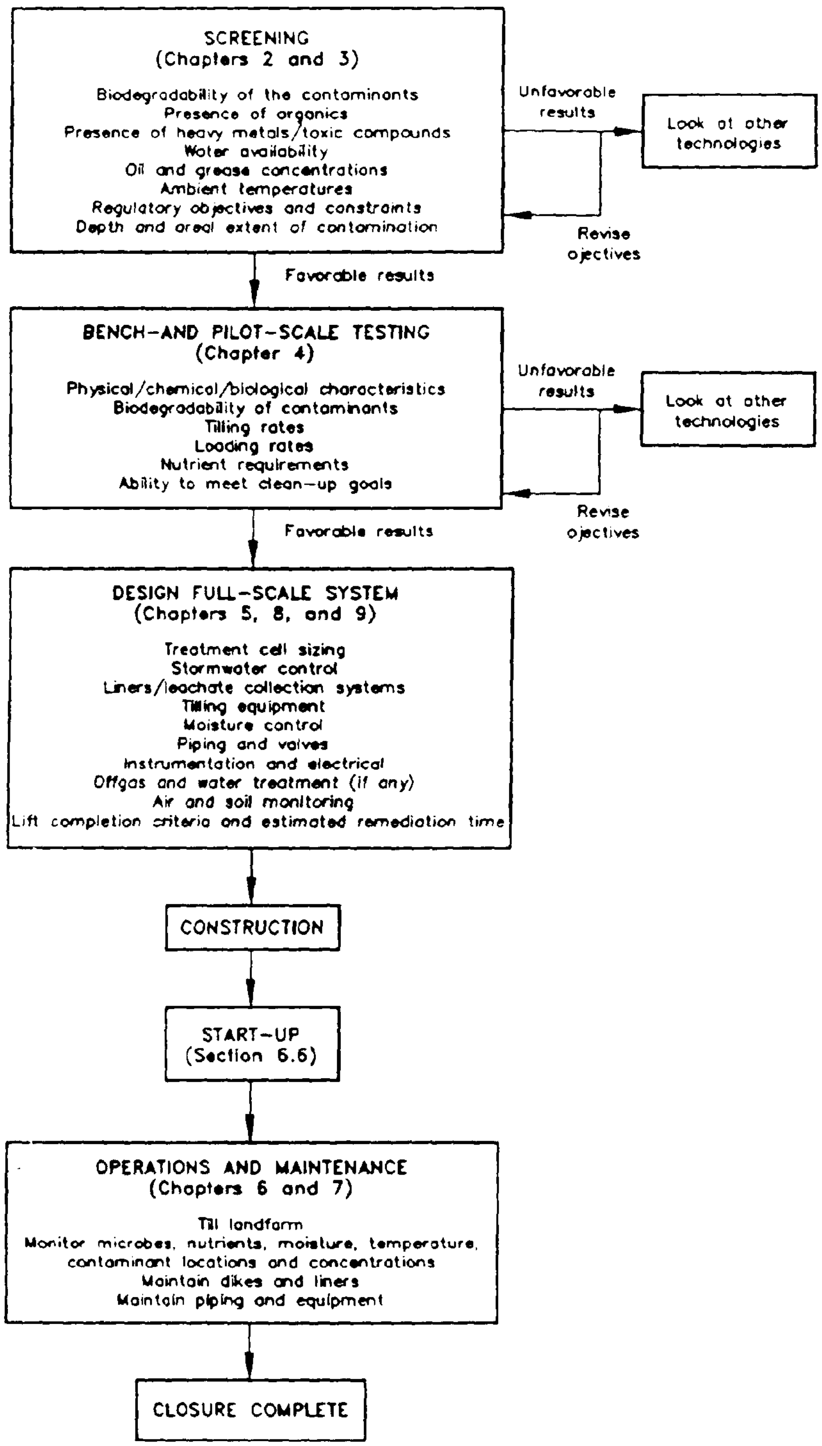


FIGURE A-1
LANDFARM APPLICATION STRATEGY

A clear distinction can be made between:

- a process which incorporates fuel products or sludges into soil to affect their treatment (i.e., "making clean soil dirty"), and

- using the process to treat soils which have been affected by fuel or other hydrocarbon spills ("making dirty soil clean")

The forms of closure required for these two types of landfarming may be considerably different. The chapters which describe regulatory requirements and closure requirements primarily focus on RCRA issues because they are national in scope and fairly consistent. Requirements for particular sites, however, may differ considerably.

1.1 PURPOSE

This Engineering Technical Letter (ETL):

- describes how landfarming is intended to work,

- provides the necessary information and procedures to evaluate applicability of the technology, and

- provides the information to properly design, specify and operate successful landfarms to treat a variety of hydrocarbon-bearing waste materials.

The ETL is intended to aid the designer and others who possess some knowledge of civil engineering, chemistry, chemical engineering, microbiology, and mathematics to select effective solutions to environmental problems for which landfarming may be a remedy.

1.2 SCOPE

The following topics are discussed in this ETL:

- Chapter 1 introduces the subject matter, presents the organization of the ETL, and describes the principles of operation, including the basis for the microbiological activity and the factors which influence the landfarming process;

- Chapter 2 discusses the applicability of the technology to a variety of wastes and sludge types, with primary emphasis on refinery products;

- Chapter 3 presents the basic regulatory requirements which must be met, and their potential impact on the operation of landfarms, including consideration of state-specific requirements;

- Chapter 4 describes the kinds of treatability studies which should be performed, the data and types of analysis used to monitor the studies, and the progression from bench-scale studies to demonstration plots;

- Chapter 5 presents the design requirements for sizing, selecting materials of construction, and providing the necessary support facilities;

- Chapter 6 discusses the operating parameters used to perform landfarming, their interrelationships and the techniques used to measure and adjust the operating parameters in the field;

- Chapter 7 presents the sampling and verification procedures used to determine when the operation has achieved its stated objectives and can either be closed or another layer of contaminated soil can be added;

- Chapter 8 describes the design and construction materials that should be used;

- Chapter 9 presents the contents and elements of a typical design and construction package for a landfarm.

1.3 REFERENCES

The reference material used in the development of this ETL as well as suggested sources of additional information are listed in Appendix C, Bibliography.

1.4 BACKGROUND

Landfarming technology was developed in the petroleum refining business. Refiners who dumped residual sludges and heavy oils from refining processes on the ground noticed that the volume of material reduced over time. Investigative work demonstrated that volatilization, dissolution into surface and ground water, sorption to the subsurface soils, and biodegradation contributed to the volume reduction. By applying nutrients, lime and water, biodegradation became the primary mechanism. The process soon became the standard method for treating many types of refinery sludges. Land "farms" were established at all major oil refineries.

Environmental legislation in the 1970s and especially, passage of RCRA in 1980, prompted a search for cost-effective methods to treat soils contaminated with hydrocarbon materials. Landfarming was one of the methods considered for site cleanups. This resulted in the following changes in landfarming practices:

- the emphasis went from applying wastes to soils to remediating contaminated soil;
- monitoring of nutrients, water, pH and chemical composition of the wastes increased;
- regulations governing the construction of treatment cells changed landfarm design dramatically; and
- cost per unit of treated material increased considerably, primarily as a result of these construction standards and monitoring costs.

Permitting and permit requirements became a part of the design and operational process. Although the process is designed to remove hydrocarbon materials from soil, air and water impacts must be monitored and controlled.

Much of the historical data for land treatment comes from experience at petroleum refineries and other hydrocarbon processing facilities, where oils and oily sludges were applied to specific areas of soil for "natural" remediation. Data from refinery landfarms is applicable to hydrocarbon remediation in soils at incidental waste sites. In 1983, the American petroleum Institute commissioned a report summarizing the data then available for refinery landfarms (API, 1983). Tables A-l and A-2 show the summarized data for full-scale and pilot-scale refinery landfarms in the United States at that time. Many of the factors discussed below were tracked in the study. The data summary includes five types of typical refinery petroleum "hydrocarbon" waste streams.

1.5 PRINCIPLES OF OPERATION

In general, microorganisms already present in soils are capable of degrading hydrocarbon materials if given the proper set of environmental conditions. These microbes will selectively grow and become more efficient in degrading the hydrocarbons, even in the presence of increasing concentrations of inhibitory materials such as metals or substituted hydrocarbons, (e.g., polychlorinated biphenyls [PCBS]). However, because not all hydrocarbon-based materials are biodegradable, the technical approach has its limits.

In some cases, special microorganisms have been successfully added to "natural" landfarm applications (e.g.,

TABLE A-1

Performance Data at Full-Scale Refinery Landfarms in the U.S.

Site	Location	Years in Operations	Annual Oil Loading		Est. Annual Oil Reduction[a]		Degradation Months/Yr	Est. Oil Reduction/Degradation Month[b]		Percent Reduction
			Barrels/Acre	lbs/ft³[c]	Barrels/Acre	lbs/ft³[c]		Barrels/Acre	lbs/ft³[c]	
A	Montana	9	70	0.98	41	0.57	6	6.8	0.09	58
B	California	2	1,900	13.35	1,460	10.28	12	122	0.86	77
C	New Jersey	8	650	7.82	455	5.47	7	65	0.78	70
D	Illinois	9	100	1.40	70	0.98	7	10	0.14	70
F	Louisiana	5	380	4.00	332	3.52	12	28	0.29	88
H	Washington	8	280	1.97	182	1.26	6	30	0.21	64
I	Texas	2	220	2.65	163	1.96	12	14	0.16	74
J	Texas	6	680	7.16	640	6.73	12	53	0.56	94
K	Texas	3	400	5.62	350	4.94	12	29	0.41	88
M	Oklahoma	12	500	6.00	400	4.80	9	44	0.53	80
N	Oklahoma	5	110	1.54	70	0.98	8	9	0.12	64

[a] annual oil reduction estimated on the basis of
$(a\text{-}b)/c$ where a = total amount of oil applied over facility lifetime (estimated)
b = oil remaining in soil (measured)
c = number of years facility has been in operation.

[b] Oil reduction/degradation month estimated on the basis of the basis of the average annual oil reduction divided by the number of degradation months/year.

[c] Pounds of oil per cubic foot of incorporation zone

Source: American Petroleum Institute, 1983.

TABLE A-2

Performance Data at Pilot-Scale Refinery Landfarms in the U.S.

Site	Location	Years in Operation	Type of Sludge	Annual Oil Loading		Est. Annual Oil Reduction[a]		Degradation Months/Yr	Est. Oil Reduction/Degradation Month[b]		Percent Reduction
				Barrels/Acre	lbs/ft^{3c}	Barrels/Acre	lbs/ft^{3c}		Barrels/Acre	lbs/ft^{3c}	
1	Ohio	3	Composite Centrifuged Oily Sludge	735	7.72	595	6.25	6	99	1.04	81
			API Separator Sludge	690	7.25	607	6.38	6	101	1.06	88
2	Oklahoma	3	Composite Oily Sludge	1140	11.97	832	8.74	9	93	0.97	73
			Composite Oil Sludge	730	7.68	569	5.99	9	63	0.66	78
			Composite Oily and Biological Sludge	540	5.67	340	3.57	9	38	0.40	63
3	Texas	3	DAF Sludge	162	1.70	152	1.60	12	13	0.13	94
			Separator Sludge	177	1.86	129	1.36	12	11	0.11	73
			Tank Bottoms Sludge	345	3.62	314	3.29	12	26	0.27	91
4	Oklahoma	2	Composite Oily Sludge	380	3.99	163	1.71	8	20	0.21	43

[a] annual oil reduction estimated on the basis of $(a-b)/c$, where:
a = total amount of oil applied over the lifetime of the facility
b = oil remaining in soil
c = number of years facility has been in operation.

[b] Oil reduction/degradation month estimated on the basis of the average annual oil.
[c] Pounds of oil per cubic foot of incorporation zone
reduction divided by the number of degradation months/year.

Source: American Petroleum Institute, 1983 for treatment of pentachlorophenol from wood-treating operations). In general, however, indigenous (native) organisms are used because inoculated organisms have a poor survival rate, while the indigenous population is adapted to the environment already.

1.5.1 <u>Microorganisms and Bioremediation</u>

The objective of landfarming is to reduce or eliminate organic compounds from a soil matrix, using microbes to either transform the compounds into compounds of less environmental concern, or to mineralize those compounds to simple compounds (such as carbon dioxide, methane, and water). The process is almost always aerobic, meaning that oxygen is the primary electron acceptor in the microbial degradation process, but almost certainly has an unavoidable anaerobic component due to the nature of the soil.

Landfarming of waste is based on the recognition that soils contain numerous and various microorganisms which degrade the myriad of simple to complex natural organic compounds from plants, animals and minerals which compose the soil. The resulting decay, humification, decomposition and weathering leads to soil formation and alteration. Microorganisms' role in this process makes them ideally suited for decomposing other natural and xenobiotic (manmade, not naturally occurring) compounds with chemical structures similar to or shared with the soil's normal components.

The land "farming" process is similar to that used for good agricultural cropping practice:

- cultivate for aeration,
- cultivate to mix soils and nutrients,
- fertilize,
- maintain water availability, and
- control pH.

All of these processes are performed in crop farming to maintain both the crop plants and the microorganisms in the soil which are essential to the health of the soil and the crop plants. In landfarming, the health and growth of the microorganisms is critical to the success of the process. The ultimate goal of the process is to degrade the organic constituents. Thus the process and its controlling parameters should be optimized based on the degradation rate of the constituents.

Degradation usually proceeds more rapidly under aerobic conditions; these can be efficiently achieved with equipment such as deep plows or rakes which "fluff" and mix the soil with air. The depth to which soil is raked or plowed is considered one "lift." Lifts range from 6 to 24 inches in depth, depending on soil type, equipment, and operating procedures. Some equipment can mix to depths of up to 48 inches in homogeneous, sandy soils, but typical lifts range from 9 to 12 inches. Deeper lifts tend to be less effective for rapid degradation because oxygen diffusion is slowed.

The intent of tillage is to establish direct contact between:

- oxygen,
- suitable microorganisms,
- the petroleum compounds of concern,
- water, and
- an adequate nutrient supply.

The process, illustrated in Figure A-2, is accomplished by bacteria, fungi, and to a lesser extent, higher unicellular organisms. Microbes typically extract energy and nutrients for cell growth by breaking down the larger organic compounds into simpler and smaller molecules, which results ultimately in mineralization.

Bacteria are approximately 14% and 3% (dry weight) nitrogen (N) and phosphorous (P), respectively. Metals and ions of potassium, sodium and magnesium are also common cellular constituents. These nutrients aid in microbial metabolism of

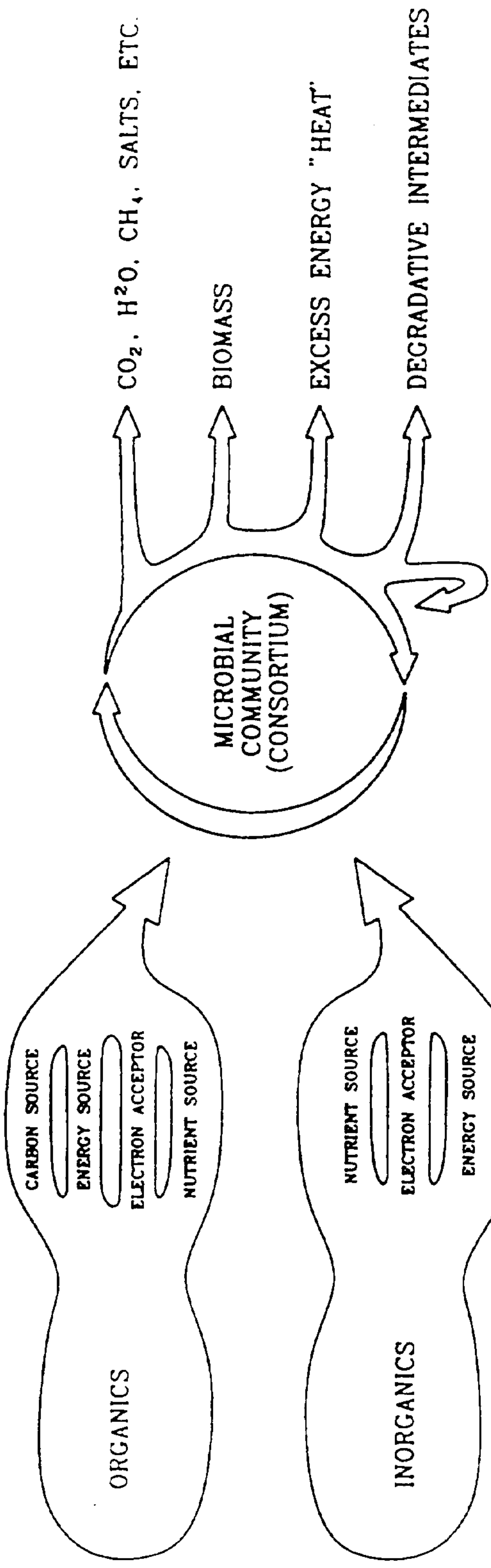


FIGURE A-2

ENVIRONMENTAL INTERACTIONS WITH THE MICROBIAL COMMUNITY

wastes and other compounds and are necessary for microbial growth. The most important nutrients are N (preferably fixed as ammonium ion or nitrogen oxides [NO:]) and P (preferably as orthophosphate for ease of assimilation by the microbes), which naturally occur in soil organic matter. However, they are not usually present in concentrations sufficient to support optimum waste degradation. Nutrient addition is usually needed to increase degradation rates.

Micronutrients, (i.e., metal cations) are also necessary for effective microbial growth and waste degradation. Most soils have sufficient natural micronutrients to support the landfarming process.

Typically, tropical soils can present several problems for biological treatment of sludges. Soils subjected to monsoonal rains often consist of oxisols, aristisols and/or volcanic ashes. Experience with the landfarming of refinery sludges in tropical West Africa and Southeast Asia suggest that:

- The use of oxisols as incorporation zone soils should be avoided. These hydric soils lack the workability and micronutrients to be of long term use.

- Aristisols may be used with proper amendment. These soils constitute many of the commonly available agricultural soils within the area. However, because of excessive leaching from monsoonal rains, many of these soils lack the micro-nutrients required to sustain a biomass considerably larger than that normally found in agricultural soils. These soils also lack the required buffering capacity to prevent significant changes in pH. These deficiencies may be overcome with the addition of ash from the burning of agricultural wastes and the addition of carbonaceous amendments to supplement the micronutrients and improve the soil's buffering capacity, respectively.

- Soils derived from volcanic ashes are commonly used in land treatment applications. These soils can provide good drainage and workability characteristics during wet weather. However, these soils often require mixing with more "loamy" type agricultural soils in order to provide sufficient "clay-sized" fractions required to increase the available surface area. Additionally, because these soils are relatively sterile (contain very little natural biomass), an inoculation of the proper microbiological consortium may be required. This can be achieved with the addition of sludges from municipal activated sludge plants, the addition of agricultural mulches from composting facilities or other aerobic degradation biomass sources.

As with any biochemical reaction, microbial metabolism is temperature-dependent. Conventional wisdom holds that the effective, practical biodegradation process essentially stops at or below 10°C (50°F); acceptable degradation rates occur above 21°C (70°F), and the temperature range of 32-38°C (90-100°F) is considered optimal. However, microorganisms may perform degradation at lower temperatures if they are acclimated. Higher operating temperatures are encountered in composting processes.

Aerobic degradation processes usually produce carbon dioxide as a principal product, and acidic organic intermediates or end products. This can render soil pore water acidic if complex buffering counter ions are not present. Monitoring and control of pH is necessary so the soil does not become so acidic that the microbes become inactive or die. Hydrated lime ($Ca(OH)_2$) is the usual agent used to control the pH in the landfarm. Other available pH control additives are further described in Section 6.4.3.

1.5.2 Unit "Processes"

Landfarming can be viewed as a series of unit processes which combine to produce remediated soils. The unit "processes" necessary for biodegradation to occur in a land treatment cell are as follows:

- source of organic carbon (FEED)
- sufficient nutrients must be provided, monitored and controlled (FEED);

- a source of water must be applied, monitored and controlled (DILUENT/SOLVENT);

- Introduction of oxygen (or an other electron acceptor) (MIXING/AERATION);

- pH monitoring and control (pH CONTROL);

- where practical, monitor and control soil temperature to above 70°F (TEMPERATURE CONTROL).

The measurement and monitoring of land treatment systems involves:

- controlling parameters: those used to control the process, and

- indicating parameters: those used to indicate process performance.

The principal Controlling and Indicating parameters are listed in Tables A-3 and A-4, respectively.

1.5.3 Controlling parameters

Controlling parameters are those constituent concentrations or environmental conditions which act to limit the landfarming process and which can be manipulated to optimize the degradation of the waste's constituents.

Nutrients and Nutrient Balance. The "crop" being grown in landfarming is microbes. The appropriate nutrient balance for

Table A-3

Landfarming Controlling Parameters

Controlling Parameters	Purpose of Controlling Parameters
Nutrient content and balance	Adequate supply to: Maximize microbial population Optimize metabolic processes
pH	Control: Optimum for microbes Immobilize metals Nutrient/substrate availability
Tillage	Entrainment of air Optimum dissolved oxygen in solution Mixing/distribution of nutrients, moisture, microbes, substrate
Moisture	Insure adequate water for: Microbial processes Delivery of nutrients Maintaining tillability/soil properties
Oxygen (Electron Acceptor)	Optimize degradation kinetics
Temperature	Optimize degradation kinetics
Hydrocarbon Dose Rate (if applicable)	Optimize substrate availability/degradation kinetics

Table A-4

Landfarming Indicating Parameters

Possible Indicating Parameters	Purpose of Indicating Parameters
Collective Organic Parameters (e.g TPH, TOX, TOO, O&G)	Rate of degradation of general substrate as indicator of general remediation rate
Carbon Dioxide in Soil Gas	Indication of aerobic degradation
Specific Chemical Constituents	Rate of degradation of target compounds indicating specific remediation rate
Microbial Enumerations	General indicator of health of microbial population
Oxygen Uptake Rate (OUR)	Indicator of aerobic metabolic consumption of oxygen and the general “health” of the microbial consortium. Potentially use in estimating the rate of hydrocarbon degradation
MICROTOX Relative Toxicity (or other general toxicity tests)	indicator of detoxification of waste as a measure of remediation progress

their good growth can be approximated from the microbes' composition. However, just as microbial growth is <u>not</u> instantaneous, the requirement for specific nutrients is not instantaneous. These nutrients can be continuously applied at levels matching the microbial growth rate, or to match the microbes organic carbon consumption rate. Higher initial applications may be appropriate to stimulate the initial burst of growth and induce various metabolic processes.

Degradation of wastes and consequential microbial growth are biochemically dependent on enzymes and structures which are polymers of amino acids and non-proteinaceous cell constituents with N as a component (such as DNA, RNA and others). proteins contain one or more amino groups and are typically 14-16% N by weight. Since proteins make up about 50% of the bacterial cell's dry weight, protein and N are critical to the growth and health of the microbes. If the organisms are deficient in available nutrient N, microbial metabolism and growth are inhibited or stopped.

Similarly, phosphorus is an integral component of many cell membrane structure lipids, cellular energy transferring molecules such as ATP, GTP, CTP, and DNA and RNA, the genetic polymers of all cells. If P is deficient, synthesis of these compounds is limited and the cell will not grow and reproduce.

Section 6.4.2 (Nutrients) describes the desired concentrations and ratios of N and P to the amount of carbon present as TPH or Oil & Grease.

In practice, N and P concentrations as available forms (NH_4, $N0_3$, $N0_2$, $P0_4$) are monitored in the field. To avoid local overloading and undesirable pH effects, a fraction of the theoretical dose is applied several times during the treatment to permit efficient use of the fertilizer. Agricultural or garden fertilizers are effective sources of N and P for landfarming.

<u>pH</u>. A pH between 6 and 8 standard units (SU) in a soil/water matrix is needed for rapid land treatment processes.

The buffering of the system (resistance to large pH changes from acid or base concentration) should be adequate to prevent sudden pH changes which can slow the degradation process. Rapid pH changes can temporarily inhibit the microbes that degrade waste constituents. Buffering capacity is an estimate of the amount of base or acid which can be added without a sudden or significant change in pH. The buffering capacity is a better parameter for judging the time and quantity of base or acid to add to the system to adjust pH.

If the matrix contains a relatively high concentration of heavy metals, the higher end of the pH range (7-8) may serve to keep the metals in a relatively insoluble form reducing their availability and potential toxic effects on the process and leachability. Additional discussion of the effects of pH on metals is included in section 2.3.2.1.

Tillage. Tilling (cultivation) of the landfarm mixes the soil, waste, nutrients, water, microbes and oxygen into the soil/water matrix. This may be performed using deep rakes, plows, rototillers, or tractor and disc sets, depending on the required depth of the lift, the soil type, the homogeneity of the soil matrix, and the size of the treatment cell.

Tilling frequency depends on the soil tillability, the soil matrix texture, its ability to drain water and entrain air, and the rate of biodegradation. Tilling frequently to enhance soil oxygenation is desirable. Typical frequencies range from three times per week to monthly. Overtilling, particularly with certain soil types or with aggressive implements, can and has been known to destroy tilth or loft of soils, effectively destroying the desirable soil properties and inhibiting remediation. Also, tilling soils with moderate to high clay contents can lead to the formation of "clods", which upon drying will be very hard and difficult to penetrate.

The tilling frequency is determined by experience and observation of the soil. After tilling, the soil loft produces a "fluffed" appearance which is the ideal state for aeration. Moisture penetration after rain or watering will minimize this loft and may require another tilling. If the soil tilth is destroyed as described above, the soil will need to be amended with manure or straw to improve the soil properties.

Moisture. Microbes cannot usually access waste constituents, nutrients or oxygen if those materials are not dissolved in water. The cells must also maintain water within the cell or the concentrations of internal salts, organics and other dissolved species will increase to the point of precipitation and damage to the cell metabolic systems. Many of the enzymes responsible for transporting nutrients and waste constituents into the cells are physically stable only when hydrated (surrounded by water).

The optimal water balance of the landfarming system is actually variable, depending on the soil's affinity for water. If the microbes cannot retain water and lose it to the soil particles, the degradation process will slow or stop. Excess water can fill the soil pore spaces and prevent air entrainment and infiltration. Excess water can also leach out many of the nutrients and carry them vertically below the cultivation zone. See Section 6.4.1 for target moisture content ranges.

Water is typically added to the treatment cell using a pump from a collection sump or tank, and hoses with sprinklers to disperse the water across the cell. In some designs, nutrients may be added to the water in the collection tank prior to sprinkling to assure complete dispersal of the nutrients.

Field water measurements utilize a variety of tensiometers or moisture meters which measure soil water content on several bases, such as soil suction, resistivity or conductivity. Methods of moisture content measurement are discussed in further detail in Section 6.4.1.

Alternate Electron Acceptors. The amount of energy available to microorganisms is, in part, a function of the electron acceptor used. All other factors being equal, relative energy available from electron acceptors is: $0_2 > N0_3 > S0_4 > CO_2$. Microorganisms usually derive energy via transfer of electrons from electron donors to electron acceptors. Electrons are usually generated during oxidation of organics (electron donors) Under aerobic conditions, oxygen is the preferred electron acceptor. Under anoxic or anaerobic conditions, $N0_3$, SO_4, or CO_2 may serve as electron acceptors. Iron and other organic compounds may also serve as electron acceptor under anaerobic conditions.

Nitrates are highly soluble in water and readily leach from soils, so releases of nitrates to ground or surface water supplies become a regulatory concern and places additional limits on the use of nitrates in landfarming applications.

Other potential electron acceptors, such as sulfate, also require anaerobic conditions. The end product of sulfate reduction, hydrogen sulfide, is both a nuisance odor and a toxicity issue.

Other. In practice, the only way to control the operating temperature of a landfarming system is to enclose it in a climate-controlled building. This also permits better control of the soil moisture and hence other operating control parameters. In colder, very dry or rainy climates, the expense of the building may be more than compensated by the improved degradation rates.

For landfarming systems where solid or liquid wastes are applied to soil, the rate of application is also a control parameter. Adding wastes too frequently or at too high a "dosage" may inhibit nutrient and oxygen transport to the microbes and may also create toxic effects. Adding wastes too slowly or in too low a dosage may starve the system for carbon, cause the microbial population to shrink, and not provide optimal degradation rates.

1.5.4 Indicating Parameters

Indicating parameters are those measurements which monitor the progress of treatment and the system's response to changes in the controlling parameters, but are not directly changed or controlled themselves.

Several measurements should be taken during landfarming to indicate directly or indirectly how successfully the microbes are transforming or mineralizing the waste. These consist of:

- collective hydrocarbon content measurements,
- air emission measurements, and
- microbial enumeration methods (e.g., plate counts),

Collective Hydrocarbon Content. Collective hydrocarbon parameters include:

- Total Petroleum Hydrocarbons (TPH or TPHC),
- Hydrocarbon Oil and Grease (HO&G),
- Total Organic Carbon (TOC), and
- Purgeable Organic Carbon (POC).

These methods (other than TOC) are based on extracting the hydrocarbon materials into a solvent and measuring the hydrocarbon content of the solvent mixture through a detector system (usually IR or GC). The methods differ in the detection method and choice of solvents. TOC is measured by oxidizing the sample and measuring the carbon dioxide produced in the oxidation.

The measurement of collective hydrocarbons is particularly useful when dealing with fuel spills or sludges, where the mixture may contain hundreds or thousands of specific hydrocarbon compounds. As the treatment progresses, the hydrocarbon content should be reduced as progress toward mineralization occurs. It is not generally practical to track the degradation of fuel products by chemical constituent, but a collective parameter allows the progress to be measured in a general way.

Air Emissions. Air samples serve three purposes in landfarming:

- to verify compliance with any site air monitoring plan;

- to measure hydrocarbon emissions for material balance calculations; and

- to measure the carbon dioxide concentration in or above the treatment cell which can be used as an index of microbial respiration.

Air monitoring plan and emissions requirements are determined on a site-specific basis and should be verified prior to developing or implementing the monitoring plan. These tests may be performed using field instruments and meters, or by collecting air samples for laboratory analysis.

Air monitoring requirements should be determined during the design phase so that appropriate air monitoring specifications can be written. The air monitoring plan will be developed from the designer's air monitoring specification.

Microbial Enumeration. Microbial enumerations are conducted to demonstrate the response of the microbial population to the favorable conditions created for the degradation of wastes by the amendment of the controlling parameters. Serially diluted samples of soil and/or water are spread, poured, or placed evenly over a source of nutrients (usually an agar stabilized gel of nutrients and organic carbon sources) on plates (usually Petri dishes) and incubated at a set temperature for a given period of time from 2 to 14 days. The number of microbial colonies visible on the plate is counted and the number of colony forming units (CFUs) from the dilution on a per ml or gram basis is calculated. The numbers are often presented in powers of ten (hundreds, thousands, millions, etc.) to simplify reporting and recognize some of the uncertainty in the method. Statistical methods may be applied to report a Most Probable Number (MPN) technique of viable microbes using broth-filled test tubes and serial dilutions. The result is an indicator of the number of heterotrophic bacteria per gram of soil.

The dilution plates of microbes may also be incubated under a specific hydrocarbon atmosphere (e.g., gasoline), or with hydrocarbons (e.g., motor oil) suspended in the agar or broth, to determine the relative population of specific functional species such as those capable of degrading hydrocarbons.

It is critical to recognize the limitations of these counting systems: they are useful in a relative sense only; (i.e., initial versus 2 weeks versus 3 months, etc.). They are not absolute measures of microbial activity or ability to degrade wastes. They only indicate relative potential and relative changes in specific populations from time to time using the same counting techniques. Standard plate or broth counting methods use rich, specially created media to grow the greatest number of organisms, but they do not grow all of the viable organisms present and do not demonstrate the microbial community's ability to degrade the waste constituents. They are a relative indicator of the soil or water system's health and suitability for microbes in general.

Similarly, "hydrocarbon" plate or dilution methods are not definitive for all the constituents of the waste. For example, diesel fuel contains a variety of similar and dissimilar constituents. Microbial growth with one or more constituents does not indicate or guarantee growth with the remaining compounds. consequently, plate or broth counts with the wastes as "food" can reflect growth on only one or a few constituents. Only disappearance of the collective waste constituents is definitive.

1.6 ADVANTAGES AND DISADVANTAGES OF LANDFARMING

For comparison purposes, the advantages and disadvantages of landfarming are listed in Table A-5.

TABLE A-5
Advantages and Disadvantages of Land Treatment

Topic	Advantages	Disadvantages
Economics	Land treatment is one of the most economical mechanisms for treating *biodegradable wastes*. *Treatment costs for general TPH wastes are routinely* $15 to $30 per cubic yard.	Containment of run-off and leachate through the construction of liners and wastewater containment, storage and treatment systems can add significantly to the cost of the treatment alternative. The space requirements of most landfarm processes are already much larger than other treatment technologies and the cost of additional acreage may be prohibitive.
Effectiveness	Land treatment is effective for **appropriate** wastes and can, when well designed and operated, destroy the constituents of concern readily and to concentrations which are protective of human health and the environment.	Certain wastes cannot be treated in landfarm applications due to regulatory restrictions, undesirable residuals, non-biodegradability, and other factors. Consequently, the range of treatable wastes is narrower than for other applications such as incineration or tank slurry processes where residuals can be recovered and treated.
Destruction of Wastes	Land treatment is a destructive technology, resulting in a reduction in constituent concentrations, toxicity, and volume of wastes.	Despite good landfarm design and the selection of wastes for treatment which contain minimal salts and metals, with many years of use and multiple applications of wastes, pH amendments, fertilizers and even "hard" water, undesirable residuals can accumulate in the soils, potentially to concentrations which may progressively interfere with the treatment process or present some risk to human health or the environment.
Disposal	Landfarming may also eliminate the disposal issues of residual, albeit clean, inert solids which are the end product of many alternative processes. Those inert solids become an integral part of the soils in the landfarm and pose no risk if the process was designed and operated appropriately.	Land treatment may only be proposed as an intermediate treatment phase. As a result, if the waste contains non-degradable fractions, excavation and disposal of the incorporation zone may be required.
Technical Expertise	Land treatment is a low technology application, requiring equipment and other materials which are commodity goods readily available in the suburban or rural areas of the country. The day to day process is well understood from both a direct applications standpoint and from related processes such as general agricultural practices. There exists a large data base of past experience and guidance from the many landfarm operations historically utilized in the refinery and petrochemical industries as well as in remedial projects. *Operations personnel need only moderate education and training.*	Good practice requires chemical and microbiological skills for testing and monitoring
Operations	ease of operation the simplicity of operation and control philosophy *the general inherent safety of the process*	In general, degradation (or destruction) rates are slower for landfarming than for *some other biological processes such as slurry phase biotreatment. This is due* to a variety of factors including mass transfer of nutrients and oxygen, waste distribution, temperature control and mixing intensity.

TABLE A-5
Advantages and Disadvantages of Land Treatment

Topic	Advantages	Disadvantages
Containment of Wastes	Newly constructed and well managed landfarms may be closed with all the soil left in place. Post-closure monitoring is normally required only for RCRA regulated sites	A greater disadvantage than residuals which remain in place are those wastes and constituents which migrate from the LTU by air emissions (including particulates), leachate migration, or surface water run-off. Because of the open nature of landfarms and the mechanical tillage of the wastes and soils, gases, vapors, aerosols or other particulates can be easily emitted without proper care and operational practices. Most landfarms historically have not been lined with synthetic liners and depend on the interaction of the soils and wastes and the dynamics of the treatment process to prevent leachate migration to the groundwater Even lined landfarms may release leachates through inadvertent defects in the liners. This is evidenced by the many lined landfills which routinely leak leachate. In the case of landfarms with routine applications of water (and precipitation due to their open nature), the hydraulic vertical driving force for leachate formation is relatively constant and potentially large.
Public Relations	Landfarming can also be a positive public relations issue as a result of the almost inherent understanding and acceptance of "farming" by the public at large.	Landfarms, particularly when poorly operated, overloaded, and odorous, can be disadvantageous when compared to other technologies with containment or smaller visibility. Residuals can prevent or limit the use of such lands for recreational or agricultural purposes by preventing the growth of crops, grass or other vegetation. Such areas can be considered a nuisance and their appearance can exacerbate any existing public relations issues for the operators.

2.0 LANDFARMING/LANDFARMING APPLICABILITY

Landfarming is not applicable to all wastes (e.g., those with little or no organic content). Even for highly organic wastes, certain classes of wastes can not or should not be landfarmed due to various constraints. These constraints may include regulations, toxicity, migration, persistence, or similar issues. This section describes the wastes and related factors which should be considered for applicability of landfarming as an appropriate technology for treating a particular waste or waste constituents of concern. Included are examples and discussions of specific waste types which should not be land treated. This section also includes information on treatable wastes and issues which need consideration for successful treatment.

This section is meant as guidance. Note that regulatory issues which make landfarming appropriate or inappropriate when it might otherwise be excluded or included are presented in Section 3.0. Table A-6 lists a variety of general guidance documents with additional information on bioremediation technologies in general and landfarming.

2.1 HISTORICAL USE AND APPLICABILITY MATRIX

Landfarming, when well-designed and operated for appropriate wastes, is an economical and safe method for treating contaminated soils. Landfarming has, at times, also been used as *de facto* land (or air) disposal, with the application to landfarms of wastes which were highly volatile or otherwise mobile, refractory to biodegradation, toxic, or cumulative.

Such applications present long- and short-term hazards to human health and the environment, and are an economic and regulatory liability to the operators and disposers. Examples of such wastes (and constituents) are certain metals, inorganic salts, refractory organics such as chlorinated dioxins, and dibenzofurans. Table A-7 lists examples of categories of

TABLE A-6

General Bioremediation and Landfarming Guidance Documents

Documents
“Contaminated Soils - Regulatory Issues and Treatment Technologies," *The Hazardous Waste Consultant*, 4.1—4.24, (Sept/Oct 1991)
“Guidelines for Land—Treating Hydrocarbon—Contaminated Soils,” *Journal of Soil Contamination*, 3(3) :299—318 (1994)
American Petroleum Institute. 1987. *Land Treatability of Appendix VIII Constituents Present in Petroleum Refinery Wastes: Laboratory and Modeling Studies* API Publication No. 4455, Washington, D.C.
Atlas, R.M. ed. 1984. Petroleum Microbiology (New York:McMillan Pub. Co.)
Baker, K.H., and D.S. Herson. 1994. *Bioremediation* (New York: McGraw-Hill Inc.).
Environmental Research & Technology, Inc. (ERT). 1985. *The Land Treatability of Creosote/Pentachlorophenol Wastes*. Prepared for Koppers Chemical Co., Inc.
Fuller, W.H.,and A.W. Warrick. 1985a/b. *Soils in Waste Treatment and Utilization*, Volumes I and II (Boca Raton, Florida:CRC Press Inc.).
Loehr, R.C. and J.F. Malina eds. 1986. “Land Treatment, A Hazardous Waste Management Alternative,” Water Resources Symposium Number Thirteen, (Austin:University of Texas at Austin).
Smith, M.A. ed. 1985. *Contaminated Land, Reclamation and Treatment* (New York:Plenum Press).
Streebin, L. E., et al. *1984. Land Treatment of Petroleum Refinery Sludges* R.S. Kerr Environmental Research Laboratory, Office of Research and Development, USEPA, NTIS PB85-148708 (1984).
U.S. Environmental Protection Agency. 1992b. *Bioremediation of Hazardous Wastes* Office of Research and Development, USEPA, EPA/600/ R-92/126.
U.S. Environmental Protection Agency. 1983. Bioremediation Using the Land treatment Concept. EPA/600/R-93/164

TABLE A-7

Waste Categories Not To Landfarm

Wastes/Constituents	Rationale for Not Landfarming	Examples of Waste Occurrences	Comments
Chlorinated Dioxins	Not routinely biodegradable Persists in the soils in original or modified forms Regulatory proscription	Paper bleaching wastes Waste Oils Thermal processing ash and residue	Recent claims of biotreatment of these wastes involve application of strain(s) of White Rot fungi, *Phanerochaete* sp.; process still under evaluation. Can be transformed to more mobile, soluble forms.
Heavy Metals Arsenic Cadmium Chromium Copper Lead Mercury Selenium Silver	Not biodegradable Accumulate in the soils May be highly leachable impacting groundwater Biotransformable in some cases to more mobile or bioavailable forms May bioaccumulate High concentrations can inhibit landfarming biological process	Waste oils Tank bottoms Process bottoms Hydrocarbon sludges Wood treating wastes (CCA) Metal processing/plating sludges	Some accumulation of heavy metals is expected in landfarming but direct application of wastes with high concentrations of metals should be avoided.
Salts Transition metal salts (such Sodium Chloride) Heavy Metal Salts (such as lead sulfate, cobalt chloride)	Not biodegradable Accumulate in the soils May be highly leachable impacting groundwater May include heavy metals concentrations High concentrations can inhibit landfarming biological process High concentrations can alter soil physical and chemical properties	Neutralized acids and bases Deliming/water softening/metals precipitation systems sludges Produced water (E&P) sludges and scale Metal processing/ pickling wastes and sludges Numerous inorganic chemical processes	As above some accumulation of salts and associated heavy metals is expected in landfarming but direct application of wastes with high salt or metal applications should be avoided. If salts are part of wastes already in place, land treatment of the organics may be appropriate as a treatment or pre treatment depending on site and regulatory factors.

TABLE A-7

Waste Categories Not To Landfarm

Wastes/Constituents	Rationale for Not Landfarming	Examples of Waste Occurrences	Comments
Radioactive Wastes	Not usually biodegradable if non-organic May accumulate in soils May bioaccumulate Radiation health hazard	Mixed wastes Produced water (E&P) sludges and scale	Radioactive inorganic constituents such as salts and metals accumulate in the soil. Degradable organics would need to be assessed for chemical and radiation emission potential both and before and after degradation. Degradation will not ameliorate radioactivity of emitted or accumulated elements.
Land Disposal Restricted (Land Banned) Wastes (Listed and Characteristic)	Regulatory Numerous wastes and reasons for restrictions (reason for listing or characteristic is described in appropriate regulations, preambles and supporting documents - see 40 CFR 268: Land Disposal Restrictions)	Listed and certain characteristic wastes	Many of the land disposal restricted (LDR) wastes (listed or characteristic) can be land treated if achievement of BDAT criteria can be demonstrated. Some LDR wastes can not be land treated under any circumstances. See Section 3 on land treatment regulations.

wastes for which landfarming should generally not be considered.

Comments on why these wastes should generally not be landfarmed, excluding regulatory issues, are included. The list is not comprehensive, but is to provide guidance on the rationales for not treating certain types of wastes. Some of the wastes in Table A-7 have been land treated in the past. Thus, historical practice is not always a guide to current good practice.

Instances in which exceptions may allow landfarming of otherwise excluded wastes include:

- Treatments approved under CERCLA RODs, Consent Decrees, RCRA corrective actions, etc.,

- Existing releases to soils, treated in place,

- Risk-based applications using site-specific or other assessment approaches.

Table A-8 is an applicability matrix. The matrix presents the types of wastes and constituents which have been historically treated by landfarming. Comments are provided on the current view of the applicability of landfarming to these materials. Table A-8 is not comprehensive but is intended to be a guide to the range and types of wastes which can be treated in landfarming applications.

2.2 TREATABLE WASTE CLASSIFICATIONS

Generally, wastes treatable by landfarming are organics. A few inorganics can be utilized by the microorganisms as nutrient sources. Most natural and many xenobiotic organic compounds can be degraded by some microbe or microbial community. Inorganics, other than as nutrient sources, are generally non-biodegradable since these metals and salts are generally in simple molecular or elemental states. However, their oxidation and reduction states can be changed

TABLE A-8

Historical Applicability Matrix

Waste Type	Typical Treatable Ranges (mg/Kg)	Potential % Degradable Ranges	Associated Issues
"Petroleum/Hydrocarbon Oil and Grease" (PO&G/HO&G)	<100 - 80,000 (dependent on composition)	>99 - <50 (dependent on composition)	Generic designation for a mixture of petroleum and/or other hydrocarbon oils and greases as measured by various analytical procedures. Fraction(s) of hydrocarbons actually present and/or detected may vary greatly depending on the extraction and analytical methods. Can be interferences for PO&G from non-petroleum hydrocarbons (natural plant and animal oils and greases) even with pre-treatment of laboratory samples.
Total Petroleum Hydrocarbons (TPH)	<100 - 80,000 (dependent on composition)	>50 - <99 (dependent on composition)	Generic designation for a mixture of petroleum hydrocarbons as measured by various analytical procedures. Fraction(s) of hydrocarbons actually present and/or detected may vary greatly depending on the extraction and analytical methods. Can be interferences from non-petroleum hydrocarbons (natural plant and animal oils and greases) even with pre-treatment of laboratory samples.
Produced Water Wastes	<100 - 80,000 (may be limited by salt content)	50 - 80 (dependent on composition)	Usually have concentrated brine (high salt) associated with hydrocarbons. See comments below for crude oil and condensate.
Crude Oil	<100 - 80,000	50 - 80 (dependent on composition)	Variable % degradation dependent on crude oil type, analytical method, and extent of heavy ends
Condensates	<100 - 10,000	90 - >99 (dependent on composition)	Variable but light composition. Volatilization may be significant for lighter fractions.

TABLE A-8

Historical Applicability Matrix

Waste Type	Typical Treatable Ranges (mg/Kg)	Potential % Degradable Ranges	Associated Issues
Gasoline	<100 - 10,000	90 - >99 (dependent on composition)	Variable but light composition. Volatilization may be significant unless weathered.
Diesel Fuel	<100 - 50,000	90 - >95 (dependent on composition)	Some odor and volatiles issues. Repeated applications and weathered fuels may result in more concentrated heavy ends.
Fuel Oil #2	<100 - 80,000	>90	Some odor and volatiles issues. Repeated applications and weathered fuels may result in more concentrated heavy ends. The degree of timely remediation is dependent on the original concentration in soils.
Fuel Oil #4	<100 - 80,000	50 - 80	Little odor and volatiles issues. Repeated applications and weathered fuels may result in more concentrated heavy ends. The degree of timely remediation is dependent on the original concentration in soils.
Fuel Oil #6 (Bunker "C")	<100 - 80,000	40 - 60	Little odor and volatiles issue. Significant portion of hydrocarbons will persist as a residual of high molecular weight analytically unresolvable hydrocarbons using standard techniques.
Kerosene	<100 - 50,000	90 - >95	Some volatilization, smaller aromatics can be major constituents, but good biodegradability.
Lubricants	<100 - 80,000	50 - 80 (dependent on composition and additives)	Composition dependent. Care should be taken that metal and other additives are not inhibitory or resistant to degradation.
Hydraulic Oils	<100 - 80,000	50 - 80 (dependent on composition and additives)	Synthetics and additives may reduce the biotreatability of these wastes but the true hydrocarbon content is typically biotreatable.

TABLE A-8

Historical Applicability Matrix

Waste Type	Typical Treatable Ranges (mg/Kg)	Potential % Degradable Ranges	Associated Issues
Motor oils	<100 - 80,000	80 - >95 (dependent on composition, additives and use)	Synthetics and additives may reduce the biotreatability of these wastes but the hydrocarbon content is typically biotreatable. Used motor oils are typically more difficult to degrade due to composition changes, metals, etc.
F037/F038 Listed Sludges	<100 - 80,000	70 - >95	Land treatment ("disposal") is banned. Metals and migration (volatile emissions and leachate) were regulatory driving force.
K48-K52 Listed Sludges	<100 - 50,000	70 - >90	Land treatment ("disposal") is banned. Metals and migration (volatile emissions and leachate) were regulatory driving force.
Waste Oils	<100 - 80,000	50 - >95 (dependent on composition, additives and prior use)	Metals, PAHs, and chlorinated hydrocarbons in used and blended waste oils led to regulatory guidelines on treatment of these wastes. Caution should be taken to determine composition.
Polycyclic Aromatic Hydrocarbons (PAH) or Polynuclear Aromatics (PNA) also carcinogenic PAHs or PNAs (cPAH/cPNA)	<10 - 10,000	25 - >95 (dependent on composition and concentrations of various PAHs)	Some volatilization with members of the naphthalene compounds. Progressively longer half-lives as the number of aromatic rings and molecular weight increases. Benzo(A)pyrene (B(a)P)(5 aromatic rings) has a bioremediation half-life typically >90 days. PAHs from 3 rings up to 5 rings are considered potential carcinogens and remediation criteria are often set on the basis of their concentrations. As an alternative, these cPAHs may have a B(a)P equivalency and PAH clean-up criteria be set on a total of B(a)P equivalents. PAHs are one group of the semi-volatile compounds.
Base, Neutral and Acid Extractable Hydrocarbons (BNA)/Semivolatiles	<10 - 10,000	25 - >99 (highly dependent on composition and concentrations)	Includes PAHs and other semivolatiles such as phenolic compounds, can include heavy chlorinated aromatics, etc. Many of the simple phenolics are very rapidly and extensively degraded

TABLE A-8

Historical Applicability Matrix

Waste Type	Typical Treatable Ranges (mg/Kg)	Potential % Degradable Ranges	Associated Issues
Creosote	<10 - 10,000	>85 (dependent on composition and higher PAH concentrations)	Primarily consists of non-chlorinated PAH/BNA type of compounds with major constituents listed in Table A-13. Most constituents readily degradable but increasing difficulty with increasing size and weight.
Pentachlorophenol	<10 - 2,000	50 - >99	Technical grade is mixture of penta, tetra, and other chlorophenols
The above table assumes unweathered hydrocarbons. Weathered hydrocarbons are harder to degrade because the residuals are typically the larger and/or more complex constituents which are more resistant to biodegradation. Similarly, hydrocarbons accumulated from numerous spills, releases, or applications in the same area will be proportionally higher in these same difficult to degrade constituents.			

biologically, mobilizing or immobilizing the materials. This is dependent upon the nature of the change and the compounds or elements involved and other chemical and physical factors such as pH. With some exceptions, the microbes can not modify the inorganic compounds to products which escape the soil in an environmentally benign form. Exceptions include denitrification processes that will alter $N0_2$ to N_2, but these processes are usually linked to degradation of organic materials.

Certain organic materials, while often not a risk to human health and the environment, are also not degradable in a landfarm. Examples are synthetic polymers which may degrade very slowly (if at all) but can pose a risk from associated leachable compounds such as plasticizers and dyes. Natural polymers, such as the cellulose and lignins in wood chips and sawdust, can degrade to some extent and may have beneficial properties in landfarming soil conditioning. Natural polymers may help to metabolically "drive" the degradation process, providing a natural substrate promoting microbial growth.

Degradation of low solubility compounds may be limited by the rate of dissolution rather than by biological factors.

2.2.1 Petroleum-Based Contaminants

Generally, petroleum-based hydrocarbons, if not substantially chemically modified and not too large and complex, can be degraded at reasonable rates. Size and complexity determine practical biodegradability based on many factors. Table A-9 provides a list of sources for information on how structure and complexity affect biodegradability. Best proof of biodegradability is actual past experience or treatability studies. No pattern of practical biodegradability should be assumed based on similar or isomeric structures.

Sources for this biodegradability information are included in Table A-10.

TABLE A-9

Guidance Documents for the Prediction of Biodegradability

Documents
Bleam, R.D., and T.G. Zitrides. 1992. "Fine tuning microbial strategies," *Soils*, 22 March 1992.
Boethling, R.S., and A. Sabijic. 1989. "Screening—level model for aerobic biodegradability based on a survey of expert knowledge," *Environ.* Sci. Technol. 23:6 pp. 672—679, 1989.
Desai, S.M., et al. 1990. "Development of quantitative structure-activity relationships for predicting biodegradation kinetics," *Environ*. Tox. and Chem., 9: 473—477, 1990.
Mathews, J.E., and A.A. Bulich. 1986. *A Toxicity Reduction Test System to Assist in Predicting Land Treatability of Hazardous Organic Wastes* (Philadephia:American Society for Testing and Materials).
Nirmalakhandan, N. and R.E. Speece. 1988. "Structure-activity relationships, quantitative techniques for predicting the behavior of chemicals in the ecosystem," *Environ*. Sci. Technol., 22:6 pp. 606—615, 1988.
Pitter, P. 1984. "Correlation between the structure of aromatic compounds and the rate of their biological degradation," *Collection Czech. Chem. Commun*., 49:2891—2896, 1984.
Stroo, H.F., et al. 1992. "How to predict biodegradation rates," *Soils*, 20 April 1992.
Vaishnav, D.D., et al. 1987. "Quantitative structure-biodegradability relationships for alcohols, ketones, and alicyclic compounds," *Chemosphere* 16:695-703, 1987.

Table A-10

Sources of Information on Biodegradability

Source
Howard, P. H., et al. 1991. *Handbook of Environmental Degradation Rates* (Boca Raton, Florida:Lewis Publishers).
U.S. Environmental Protection Agency Office of Research and Development (ERODE). 1982b. *Treatability Manual* (EPA 600/2-82-001a and revisions), EPA ERODE, Washington DC.
U.S. Environmental Protection Agency. 1994c. *Vendor Information System for Innovative Treatment Technologies (VISITT) data base* EPA 542-R-94-003, EPA Office of Solid Waste and Emergency Response, Technology Innovation Office.
U.S. Environmental Protection Agency. 1994a. *The EPA Risk Reduction and Engineering Lab (RREL) Treatability data base Version 5.0* (formerly WERL data base) EPA RREL, Cincinnati, OH.

Table A-11 lists some petroleum-based materials potentially treatable by landfarming. Table A-12 lists some of the chemical categories of petroleum compounds which are degradable in landfarms.

2.2.2 Analytical Considerations for Performance Monitoring
Analytical programs for hydrocarbon wastes often use collective parameters such as TPH and Hydrocarbon or Petroleum Oil and Grease (HO&G or PO&G). Similar terms used for these analyses are Total Extractable Petroleum Hydrocarbons (TEPH) or Total Recoverable Petroleum Hydrocarbons (TRPH). These useful analyses can be misleading, however, due to the different ranges of hydrocarbons detected in the various analyses due to variable extraction, clean-up, and analytical detection methods. For example, TPH methods can include small molecular weight hydrocarbons ideal for landfarming and/or very large, complex hydrocarbons taking years to biodegrade. These variables need to be understood to design the process and monitoring program. There is no ideal analytical TPH procedure.

2.2.3 Wood Preserving **Contaminants**
Three categories of chemicals have been used to preserve wood industrially:

- creosote oils (derivative mixtures from coal tar processing),
- pentachlorophenol (PCP) and related compounds, and
- metals such as chromated copper arsenate (CCA).

Sites may have several or all of the above due to combined or sequential usage. The metals can not be biodegraded but could possibly be immobilized or mobilized by biotreatment. Creosote oils and commercial PCP preparations have been both successfully and unsuccessfully biotreated. The causes of the occasional failures are not certain but appear to be related to problems with pH control and overloading the treatment system.

TABLE A-11

Potentially Treatable Petroleum Related Materials

Material Type
Exploration and Production wastes (except the brines which should be landfarmed only with complimentary treatment for salt)
Crude oil
Gasoline (including many of the blending fractions but with limits due to volatilization)
Kerosene, Diesel, Jet Fuels and many of the blending fractions Fuel Oil #2
Fuel Oil #4
Fuel Oil #6 (Bunker C Oil)
Hydraulic oils and fluids
Lubricants
Motor oils
Many substituted hydrocarbons such as amines, etc.
Heterocyclics such as pyridines, etc.
Benzene, toluene, ethylbenzene, and xylenes (BTEX)
Waste Oils

TABLE A-12

Chemical Compounds Degradable in Landfarming

Compound or Class
Alkanes (Paraffins)
Alkenes (Olefins)
Naphthenes (Alicyclics, Cycloparaffins)
Aromatics (Monoaromatics, Polyaromatics)
Naphthenoaromatics (Aromatic/Alicyclic combinations)
Sulfur compounds (Thiols/Mercaptans, Thiophenes, etc.)
Nitrogen compounds (Indoles, Pyridines, Carbazoles, etc.)
Oxygen compounds (Phenols, Cresols, Carboxylic Acids, Alcohols, Ketones, Esters, etc.)
Asphaltics (complex mix of above with N, 0, 5, etc.)

Creosote oils are distillates from coal carbonization and typically consist of a variety of aromatic constituents. Table A-13 shows the relative composition of a typical creosote oil. The oil is primarily aromatic semivolatiles with a complex mix of minor constituents such as heterocyclics and substituted semivolatiles.

Technical PCP is prepared by the catalytic chlorination of phenol and contains impurities of related by-products. PCP is usually mixed with creosote or petroleum products for wood treatment applications. Technical PCP may contain some chlorinated dibenzodioxins or dibenzofurans. PCP is primarily a free acid at lower pH and adsorbs strongly to soils. At high pH, PCP is ionized and is very mobile with increased solubility (almost completely ionized at pH 7.0)

Table A-14 shows some typical wood-treating waste matrices which are treatable by landfarming.

Loading rates should be estimated based on site-specific conditions and the results from the treatability studies. For creosote, initial application rates may be as high as 1,000 mg creosote/Kg of soil. Reapplication rates can be as high as 5,000 mg/Kg to 10,000 mg/Kg of soil per month (ERT, 1983; McGinnis, 1985).

Loading rates for PCP in landfarms may be between 10 mg PCP/Kg soil and 30 mg PCP/Kg soil, for initial applications. Prior adaptation or acclimation is critical for treating high concentrations of PCP. Reapplication rates may be > 2,000 mg PCP/Kg of soil every 3 days (ERT, 1985; McGinnis, 1985). Gradual increases in reapplication rates are appropriate.

2.3 TREATMENT CONSTRAINTS

Presented below are operational constraints on the use of landfarming. Not included are those regulatory or other logical constraints due to unsuitability of the material for

TABLE A-13

Relative Composition of Typical Creosote Oil[1]
(>1%)

COMPOUND	% BY WEIGHT
Napthalene	3.0
2-Methylnaphthalene	1.2
l-Methylnaphthalene	0.9
Biphenyl	0.8
Acenaphthene	9.0
Dimethylnaphthalenes	2.0
Dibenzofuran	5.0
Carbazole	2.0
Fluorene	10.0
Methylfluorenes	3.0
Phenanthrene	21.0
Anthracene	2.0
9, 10— Dihydroanthracene	-
Methylphenanthrenes	3.0
Methylanthracenes	4.0
Fluoranthene	10.0
Pyrene	8.5
Benzofluorenes	2.0
Chrysene	3.0
Benz (a) anthracene	-
Benz (j) fluoranthene	-
Benz (k) fluoranthene	-
Benz (a) pyrene	-
Benz (e) pyrene	-
Perylene	-
Benzo (b) chrysene	-
Other Organics	9.6
[1] Lorenz and Gjovik, 1972	

TABLE A-14

Landfarmable Wood—Treating Wastes

Matrix	Sources
Creosote or PCP contaminated soils	Process, tankfarm, drip, and finished product storage areas
Creosote or PCP sludges	Settling ponds, treatment cylinders
Shredded or chipped creosote or PCP treated wood products	Railroad cross—ties, poles, and other discarded products
Creosote or PCP oils, mixtures or preparations	Process equipment, storage tanks, free product GW recovery (NAPLs)

biodegradation or unacceptable risk to human health or the environment.

2.3.1 Biodegradability

Almost all organic compounds are biodegradable in the proper circumstances or time. The biodegradability of wastes or specific waste constituents must be defined in terms of a realistic time period determined by the goals of the treatment program. Biodegradability is the major determinant for the applicability of landfarming for a waste or particular constituent(s). Inherently non-biodegradable wastes or constituents such as metals are discussed in Section 2.3.2.

Biodegradability limits due to toxicity are a function of concentration. If the concentration of the toxicant can be adjusted or managed or the biomass is large enough, many highly toxic wastes or constituents can be biodegraded. Toxicity and toxic organics and inorganics are discussed further in Sections 2.3.2.5 and 2.3.2.6.

Management of the concentration of the waste or constituent(s) to progressively increased concentrations can challenge the microbes to degrade more waste, increasing the concentrations of waste degraded.

2.3.2 Interferences with Bioremediation Processes

A range of physical, chemical and biochemical conditions or materials can interfere with bioremediation. Major interferences are discussed below.

2.3.2.1 Metals

Heavy metals in the wastes can interfere with the necessary biological processes in the landfarm through toxic effects. Metals can inhibit various cellular processes and their effects are often concentration-dependent. Table A-15 lists some typical heavy metals and indicates those which are known to be growth nutrients as well as potentially inhibitory. Metal toxicity for microbes will usually involve specific chemical reactivity. Metals such as copper, silver and mercury are

TABLE A-15
Potentially Toxic Metals

METAL	SOME POTENTIAL SOURCES	POSSIBLE MICROBICIDE (Y/N)	POSSIBLE NUTRIENT (Y/N)
Arsenic	Refinery wastes and soils; natural gas processing wastes and soils; wood treating wastes	Y	Y
Copper	Waste oils, machining oils, process sludges, tars and residuals; wood treating wastes	Y	Y
Nickel	Waste oils, machining oils, process sludges, tars and residuals	Y	Y
Chromium	Refinery wastes; process sludges, tars and residuals; waste oils; machining oils; wood treating wastes	Y	Y/N
Cobalt	Refinery wastes; machining oils	N	Y
Zinc	Refinery wastes; lubricant wastes; wood treating wastes	N	Y
Selenium	Refinery wastes	N	Y
Molybdenum	Refinery wastes; waste oils; machining oils	N	Y
Manganese	Refinery wastes; lubricant wastes	N	Y
Lead	Tank bottoms; tank farm soils; tank terminal soils; gasoline LUST soils; drill and other pipe threading, manufacturing and cleaning facilities	N	N
Cadmium	Degreasing solvents; waste oils	Y/N	N
Barium	Oil exploration and production wastes	N	N
Mercury	Refinery wastes	Y	N
Silver	Degreasing solvents	Y	N
Vanadium	Refinery wastes; process bottoms, tars, residuals, crude oils	N	N
Y/N = Uncertain			

typically very toxic particularly as ions, while metals such as lead, barium and iron are usually benign to the microbes at levels typically encountered.

The nutrient metals are usually found naturally in the necessary amounts for plants and microbes in fertile soils. The toxicity of these metals is usually dependent on their concentrations and those conditions which affect the concentrations. The availability and/or toxicity of these metals to the microbes is usually dependent upon the pH. For additional discussion, see the pH subsection of Section 1.5.3.

Table A-16 lists some of the conditions determining metal toxicities.

2.3.2.2 Water

Microorganisms do not grow without adequate water, the universal solvent for their cellular biochemicals, growth substrates, oxygen and nutrients. Water availability can be determined as measured in the soil (field capacity, etc.). See Section 6.4.1 for target moisture content ranges and explanation of field capacity. The water activity is a measurement of the available water for the microorganisms.

Landfarming can be inhibited by total dissolved solids (TDS) concentrations in the soil water although microbial communities can acclimate for bioremediation purposes where T[)S concentrations are as high or higher than typical sea water (3.5%). Microbes thrive in marine and seashore environments with high TDS content. Exploration and production organic wastes are often bioremediated in the presence of high brine concentrations.

Excess water can be a constraint for landfarming. If the soil water concentration is very high or saturated, the soils may not till well, may cohere as large consolidated masses, water may occlude pore spaces preventing air entrainment. consequently, for efficient landfarming, water management is needed to prevent excess water in the soil. The landfarm soils

TABLE A-16

Factors Affecting Metal Toxicities for Landfarming

Factor	Mechanism(s)
Metal concentration	Controls maximum level of metal available.
pH	Varies solubility/availability. Affects ionic state. Affects the general health of microbial population. Affects transport into microbes.
Organic content of the soils	Sequesters metals.
Microbial population*s size, species/strain, metal resistances	Controls microbial population*s metabolic susceptibility and resistances. Affects relative concentrations per cell.
Water balance	Varies solubility/availability. Affects general health of microbial population.
Nutrient availability	Compete with toxic metals for entry and reaction with cell components.
Chemical form	Contributes to solubility/sequestration reactions. Affects basic toxicity/reactivity.
Concentrations of other toxicants	Affects cumulative or total toxicity. Stresses and increases susceptibility of microbes to toxic metals
Concentrations of other metals	Affects cumulative or total toxicity. Compete with toxic metals for entry and react ion/ incorporation with cell components.

may not drain adequately. The soil drainage properties may be modified by amendments of fibrous or bulky natural organics (sawdust, straw, shredded wood, etc.) or synthetic or inorganic amendments (such as gypsum, sand, polyacrylamides, perlite and pumice, etc).

Rainfall affects the performance of a landfarm by uncontrollably altering the moisture in the treatment area. Too much rain may saturate the landfarm soils, preventing air infiltration and inhibiting tillage. Biodegradation of the waste during saturated periods is reduced or halted and may produce a nuisance odor as a result of anaerobic activity. Tilling will help dry the soils, but can cause clumping.

2.3.2.3 pH

pH extremes or sudden pH changes of the waste/treatment system matrix can interfere with:

- microbial metabolism,
- gas solubility in soil water,
- nutrient availability in soil water, and
- heavy metal solubilities.

All of these factors can affect landfarming processes. Most natural environments have pH's between 5.0 and 9.0. Consequently, most microbes' preferred pH range is 5.0 or 6.0 to 9.0 (Atlas, 1984; Brock, et al., 1984a). This is a range in which most soils will naturally occur. Microbes can adapt to a broader range of pH values, but typically with an accompanying decrease in growth/metabolic rates and a reduction in the variety of microbial strains.

Fertile native soils may have natural buffering capacity due to carbonates and other minerals which can be exhausted with time and degradation because the products of the degradation may be acidic. Methods for measuring the buffering capacity of soils are included in Section 7.0 - Operating Requirements. Section 8.0 discusses some of the pH amendments used typically in landfarms.

The pH optimum for landfarming a waste may depend on waste constituents whose form, structure and solubility, and thus availability to the microbes, may change.

2.3.2.4 Toxic organics

By design, some organic compounds are toxic to targeted life forms such as insects, plants, etc. and may also be toxic to microbes. These include herbicides, pesticides, rodenticides, fungicides, and insecticides. However, such compounds are not typically present in petroleum, or petrochemical wastes. Wood-treating wastes will contain pesticides.

2.3.2.5 Toxic Inorganics

Some classes of inorganic compounds, such as cyanides and azides are toxic to many microbes although they can be degraded following adaptation. These types of materials would not typically be present in wood-treating and petroleum and petrochemical wastes in high concentrations. Nutrient sources, such as ammonia, nitrate and nitrite, can be toxic to unadapted microbes (Brock et al., 1984; Atlas, 1984a).

2.3.2.6 Temperature

Temperature is a limiting physical condition for landfarming. The biochemical, chemical, and physical processes of landfarming respond to temperature changes in the same way as routine chemical reactions. Higher or lower temperatures increase and decrease respectively the rate of the overall process. Microbes prefer to grow at temperatures in a range of about 10^0 to 38°C and when possible, the landfarm should be operated in this range (Brock et al., 1984; Atlas, 1984a). Landfarm soils act as heat sinks, and consequently, are difficult to artificially change in temperature. Low temperatures seldom kill the microbes and with warming the microbes typically recover. The effects of the expected temperatures should be factored into the design basis expected degradation rate.

2.3.2.7 Wind

Wind may enhance removal of moisture from the landfarm and may create particulate emissions and contribute to odor nuisance problems.

2.3.3 Effects of Soil Type

Landfarming is effective in a variety of soils, from sands to tight clays. The soil type affects the rate of mass transport of nutrients, hydrocarbons, water, oxygen and pH adjusters. This affects the operation of the process and the potential for migration of the wastes and amendment. Highly organic soils can be sorptive and act as a barrier to organic migration.

2.3.4 Other Physical Constraints

Anecdotal evidence suggests high concentrations of oil and grease, tar, viscous residuals, etc. can physically block the pore spaces of the soils limiting mass transfer of nutrients, water, and oxygen into the soils and "smothering" the landfarm process. A general rule-of-thumb in the environmental remediation industry is to avoid oil and grease greater than 8-10% (80-100,000 mg/Kg) without a successful biotreatability study.

3.0 REGULATORY REQUIREMENTS

This section is provided as a guide and reference to pertinent federal requirements for the landfarming of hazardous wastes, and is not intended to cover individual state regulations which may not be pertinent to all landfarming operations.

3.1 PERMITTED TSD FACILITY STANDARDS

TSDF Permit - 40 CFR 264. A Treatment, Storage and/or Disposal Facility (TSDF) is required to obtain a RCRA permit prior to treating, storing, or disposing of any hazardous waste. Specifically, Part 264 addresses landfarming permitting requirements under Subpart M, Sections 264.270 through 264.283. This Subpart addresses the following requirements:

- The treatment program must be designed to ensure that hazardous constituents are degraded, transformed, or immobilized.

- The treatment demonstration must show that the waste can be completely degraded, transformed, or immobilized.

- Design and operating requirements must maximize the degradation, transformation, and immobilization of hazardous constituents in the treatment zone.

- Food-chain crops can only be grown if specified in the permit.

- An unsaturated zone monitoring program must be established.

- Record-keeping of hazardous waste application dates and rates must be maintained in the operating record.

- Closure and post-closure procedures must be followed.

- Special requirements for ignitable or reactive waste must be followed.

- Special requirements for incompatible waste must be followed.

- Special requirements for hazardous wastes F020, F021, F022, F023, F026, and F027 must be followed.

Permits Required for Landfarming Demonstrations Using Field Test or Laboratory Analyses - 40 CFR 264.270. For each waste that will be applied to the treatment zone, the owner or operator must demonstrate, prior to application of the waste, that hazardous constituents in the waste can be completely degraded, transformed, or immobilized in the treatment zone. In making this demonstration the owner or operator may use field tests, laboratory analyses, available data, or in the case of existing units, operating data. If the owner or operator intends to conduct field tests or laboratory analysis in order to make demonstrations under this part, he must obtain a treatment or disposal permit under 40 CFR 270.63.

Design and Operating Requirements - 40 CFR 264.273.

The facility permit will specify how the owner or operator will design, construct, operate, and maintain the landfarming unit. At a minimum the permit will specify the following:

- The rate and method of waste application to the treatment zone,
- Measures to control soil pH,
- Measures to enhance microbial or chemical reactions; and
- Measures to control the moisture content of the treatment zone.

A RCRA TSD permit is not usually required for landfarming activities involving wastes that are not RCRA hazardous. An example of this is the treatment of petroleum contaminated soils resulting from the remediation of leaking underground storage tanks.

Some individual state programs regulate the landfarming of these non-hazardous wastes through an equivalent permitting process.

3.2 LAND DISPOSAL RESTRICTIONS - 40 CFR 268

The Land Disposal Restrictions (LDRs) apply to RCRA Hazardous Wastes only. When a waste is restricted, it must be either treated to below a specified concentration or treated with a specific type of technology before it can be land disposed.

For CERCLA or corrective action sites, LDRs are not applicable for on-site landfarming unless "placement" occurs. In-situ treatment and treatment in temporary containment facilities do not constitute placement.

When LDRs do apply, a restricted waste may be land disposed only if the waste meets the requirements in 40 CFR 268.40. Thus there are instances when use of landfarming for RCRA hazardous wastes may be precluded by LDR restrictions unless approval is granted which allows an alternate treatment standard to be applied.

3.3 STORMWATER DISCHARGE PERMIT - 40 CFR 122.26

Storm water discharges associated with industrial activity, including land application sites, must apply for a permit if they exceed certain surface area criteria. Few landfarms are operated in enclosed buildings or under roofs, so storm water management is a design and a permitting issue. Since most landfarms treat soil contamination, they are not intended for long-term operation. Thus, individual permits are issued to each specific facility for storm water discharges related to industrial activity. In most instances the permit is tailored to meet the discharge characteristics of the permittee and/or the specific requirements of the receiving waters.

3.4 GROUNDWATER PERMIT

Groundwater permits are issued by state agencies to regulate the addition of materials to groundwater from any facility or operation which acts as a discrete or diffuse source. Some states use language such as "may impact the waters of the state" in the applicability of the permitting requirements, which guarantees that a permit application is required. This permit may be the only regulatory mechanism available to grant the state permission to oversee the cleanup.

3.5 CLEAN AIR ACT

Designers should look to the state in which the landfarm will be constructed and operated for air quality regulations. Some, but not all, states have developed air toxics programs which will apply to emissions which are generated by landfarming operations. Designers should seek guidance from the state air quality regulators for allowable emission rates, control requirements and air quality standards for air toxics. Some states have no air toxics program. In such cases, designers will have to rely on their industrial hygiene and risk assessment personnel to determine allowable emission rates, control requirements and air quality guidelines for air toxics.

Under the National Ambient Air Quality Standards (NAAQS), there are six National Ambient Air Quality (NAAQ) contaminants. They are lead, NO_x, SO_2, PM10, Ozone (which is regulated in part by establishing emission standards for hydrocarbons) and CO. Ozone and PM10 are the only two NAAQ contaminants that could possibly be affected by landfarming operations. States are required by federal law to develop state implementation plans (SIPs) for coming into compliance with NAAQS. Designers should contact state air quality regulators to see how landfarm construction and operation fits into the state specific SIP. State air quality regulators will advise on emission standards and control technology for NAAQ contaminants from landfarming operations.

3.6 CLOSURE AND POST-CLOSURE CARE AND MONITORING

This section outlines some major aspects of federal regulatory requirements that may apply to the closure of RCRA landfarming facilities. Since local requirements and regulations are variable from state to state (particularly for non-hazardous wastes), closure requirements should be established on a site-specific basis.

3.6.1 RCRA Facility Closures

At landfarming facilities following RCRA regulations, a demonstration must be performed to show that the wastes can be gradually transformed or immobilized before landfarming operations begin. At closure, the landfarming facility must meet U.S.EPA treatment standards for land disposal to leave the treated soil in place. If these treatment standards are not achieved, the soil must be removed and disposed of as a hazardous waste.

3.6.2 Post-Closure Care Requirements

The purpose of post-closure care is to finalize waste treatment of the remaining soil while monitoring for any unforeseen long-term changes in the system. Post-closure care requirements for facilities with RCRA wastes include:

- continue operations consistent with other post-closure care activities;
- maintain vegetative cover;
- continue run-on control system;
- control wind dispersal of hazardous constituents;
- continue compliance with regulations concerning growth of food-chain crops;
- continue air monitoring on the site at its perimeter; and
- continue unsaturated zone monitoring, except that soil-pore liquid monitoring may be terminated 90 days after the last application of waste contaminated soil. Monitoring must include soil monitoring using soil cores and lysimeters.

For facilities with non-RCRA wastes, state or local regulations may require groundwater monitoring.

3.7 CORRECTIVE ACTIONS

Many hazardous waste sites undergoing RCRA corrective actions may not be subject to the RCRA Land Ban requirements since, by definition, the sites have already been subjected to uncontrolled releases of the hazardous materials. These sites undergoing corrective actions are typically allowed considerable flexibility in the design and operation of treatment facilities in order to expedite clean-up actions. For example, the design criteria for leachate collection and containment systems is highly variable. Typically, leachate collection and containment design criteria are either established by agency guidance or by risk assessment criteria. Many states offer a choice of using either method.

Utilization of the state's guidance criteria can significantly reduce design costs, but may increase construction costs due to the inherent conservative nature of the criteria. State agencies may either publish these specific design criteria or refer to EPA standards.

Utilization of risk-based design criteria increases field investigation and design costs, but may result in significant construction cost savings if alternative containment designs can be shown to provide risks within acceptable levels. Risk assessments required to justify alternative design criteria typically involve:

- determination of contaminant migration pathways through careful delineation of surface flow conditions, air dispersal patterns, hydrogeologic conditions, and human or biota access;

- determination of potentially sensitive receptors such as aquifers, receiving bodies of surface water, communities, endangered or protected species, on-site workers, etc;

- determination of maximum exposure levels for each waste constituent which result in acceptable risks for each of the identified receptors; and

- mathematical modelling of each of the transport and diffusion I dilution mechanisms (direct contact, air dispersal, surface run-off, groundwater transport, etc.) in order to determine the contaminant concentrations at the receptor location or a negotiated point-of-compliance.

Additional guidance for the development of risk-based design criteria can be found in EPA guidance documents (USEPA, 1989b; USEPA, 1989d; USEPA, 1989e; and USEPA, 1995).

4.0 TREATABILITY STUDIES

Treatability studies are done to determine the suitability of one or more technologies for the remediation or treatment of a waste. The suitability of landfarming, as determined by biotreatability studies which can involve chemical, physical, and biological studies, all focus on determining the biological treatability of a waste (see Table A-17, Guidance for Treatability Studies).

Biotreatability studies simply involve monitoring the disappearance of a waste's constituents of concern over time due to microbial activity from indigenous or exogenous (added) microorganisms. To prove that treatment is primarily biological, an accounting (mass balance) estimation of all the various mechanisms of removal is made (volatilization, leaching, chemical destruction, etc.). When done correctly, treatability studies will not only demonstrate the efficacy of the technology but provide information/data for the design of the full-scale process.

For the study data to be of use, each phase must have controls. These controls include the standard QA/QC type of processes for sampling, analysis, and data evaluation, but also experimental controls, variations of the basic test protocol. These variations provide a means of testing the hypothesis that biological processes and environmental variables or amendments can result in the removal or disappearance of the wastes. Typical experimental controls include abiotic (killed or inhibited microbes) tests, unamended tests (no nutrients, etc.), and perhaps microbial augmentation tests.

Treatability studies are usually performed in increasingly complex phases, with each phase providing information to design the next phase. This allows cessation of the effort if an earlier phase indicates that the approach is unsuitable. Typical test phases are presented in Table A-18.

TABLE A-17

General Guidance Documents for Treatability Studies

Document
American Petroleum Institute. 1987. *Land Treatability of Appendix VIII Constituents Present in Petroleum Refinery Wastes: Laboratory and Modeling Studies*, API Publication No. 4455, Health and Environmental Affairs Department, API Washington, D.C.
Barnhart, M.J. and J.M. Myers. 1989. "Pilot Bioremediation Tells All About Petroleum Contaminated Soil," *Pollution Engineering.*
Dobbins, D.C., Jr. 1994. "The Use of Parametric Statistics in Biological Treatability Studies," *J. Air & Waste Manage. Assoc.* 44:1226–1229.
Kerr, R. S. 1988. *Interactive Simulation of the Fate of Hazardous Chemicals during Land Treatment of Oily Wastes: RITZ (Regulatory and Investigative Treatment Zone) User's Guide*, Water Research Center, USEPA, NTIS PB88–195540.
Kerr, R. 5. 1986. *Waste/Soil Treatability Studies for Four Complex Industrial Wastes: Methodologies and Results Volume 1. Literature Assessment, Waste/Soil Characterization, Loading Rate Selection.*, Environmental Research Laboratory, USEPA, NTIS PB87–111738.
Korfiatis, G.P. and C. Christodoulatos. 1993. "Treatability Studies as a Remedial Option Screening Tool for Contaminated Soils," *Remediation*, Autumn 1993.
U. S. Environmental Protection Agency. 1993c. *Guide for Conducting Treatability Studies Under CERCLA, Biodegradation Remedy Selection, Interim Guidance*, Superfund Innovative Technology Evaluation, EPA 540/R–93/519a.
U.S. Environmental Protection Agency. 1993d. *Guide for Conducting Treatability Under CERCLA: Biodegradation Remedy Selection, Quick Reference Fact Sheet*, EPA 540 R-93/519b.

TABLE A-18

Treatability Process
Phases and Their Functions

PHASE	TYPICAL TYPE	PURPOSE/FUNCTION	COMMENTS
Characterization	Chemical Analyses Physical Analyses Biological Analyses	Understand the chemical, physical and biological characteristics of the waste and/or soil to assess potential needs and requirements for biodegradability and biotreatability. Determine appropriate monitoring criteria selections. Estimate acceptable loading rates for screening study. Determine if there are characteristics which exclude or make this waste and/or soil poor candidates for land treatment.	The limitation of characterization is usually an issue. Too much is expensive and too little can lead to assumptions which are later demonstrated to be false. Collecting existing information about the site soils and/or wastes can guide the selection of the appropriate characterization parameters. Collective analyses of all types (TPH, TOC, TKN, TOX, Toxicity, etc.) are very useful for alerting the designer to unexpected problems and inconsistencies with the specific data, but must be understood for their limitations as well. Loading rate studies with toxicity assays or other methods are useful for estimating the acceptable maximum concentration for the Screening Phase.
Screening Study	Shake Flask Study Other	Demonstrate biodegradability of the wastes and/or key constituents of concern. Confirm the monitoring criteria selected during characterization. Develop estimates of the potential initial loading rates of the next phase. Guide the process design for the next phase.	Loading rate studies with toxicity assays or other methods are useful for estimating the acceptable maximum concentration for this phase. However, the maximum loading rate for toxicity may be so concentrated that, with the expected degradation rate and time of operation, no significant change (difference measurable with confidence) may be detectable. Loading rates are usually compromises between the expected degradation rate, time of operation, and the toxicity level.

TABLE A-18

Treatability Process
Phases and Their Functions

PHASE	TYPICAL TYPE	PURPOSE/FUNCTION	COMMENTS
Microcosm Study	Tray/Pan Study Other	Low-cost controlled demonstration of basic biotreatability. Develop and test basic operational design concept Test monitoring criteria in solid phase. Develop basis for pilot and/or demonstration design	Used to demonstrate biodegradability of the wastes and/or key constituents of concern. If little or no indication of biodegradability, then either re-evaluate screening approach or select different treatment technology. Biodegradability can be judged based on reduction(s) in volume, toxicity and/or concentrations of the contaminants. Complete reductions are unlikely but trends which plateau or become asymptotic above targets can indicate poor degradation of the entire range of waste constituents and may call for re-evaluation of treatment approach, loading rates, amendment program, etc.
Pilot Study	Contained Pad/Box Other	Scale-up to imitative but controlled version of full-scale process. Test basic operational design concept and some operating variables while controlling others. Demonstrate biotreatability in larger less controlled setting.	Can be uncontained box or contained system at proposed full-scale site or off-site. May not be significantly different from demonstration, but may be enclosed, lined, etc.
NOTE: The full treatability process is rarely required for known petroleum hydrocarbons. Small lab and pilot field studies will usually provide the needed data.			
Demonstration	On-Site, Small-Scale, Ambient Conditions, imitative of full-scale design and operations.	Operate small-scale version of full-scale process, typically at the potential full-scale site. Demonstrate monitoring criteria effectiveness. Demonstrate the basic operational and process design's suitability with actual site conditions. Demonstrate successful biotreatment of wastes with design process and site conditions.	Typically a smaller version of full-scale design on-site with ambient conditions.

In practice, the full range of treatability studies is usually not required for petroleum wastes. More typical is a small laboratory study (to determine nutrient additions) and a small pilot program to determine degradation rates and operational factors under field conditions. More extensive studies may be required if difficulties are encountered in these simple studies.

4.1 RATIONALE

Landfarms are large investments with regulatory limits. A major purpose of treatability testing is to develop a design basis for an effective landfarming process. The complete treatability study should determine the biotreatability of the waste(s) and apply this information into an optimally designed and operated landfarm.

Treatability studies must characterize the target waste(s) and soil(s) as a treatment matrix, identify basic biodegradability of the wastes (no unknown factors limiting degradation), confirm biotreatability of the wastes (safe, controllable, predictable, effective treatment), and operate a large pilot and/or an on-site small-scale demonstration (to show scale-up in the field). The results of the treatability study should be judged on three criteria: (1) toxicity reduction, (2) volume reduction, and/or (3) constituent concentration(s) reduction.

A treatability study should assess the effects of controlling parameters (pH, moisture, nutrient concentrations, etc.) and monitoring parameters (analyses for waste constituents or collective parameters such as TPH). See Table A-19 for some of the key data sought in a treatability study for a full-scale design.

4.2 WASTE/SOIL CHARACTERIZATION

Waste and soil characteristics are critical to development of a treatability design and the full-scale landfarm process design. The most significant characteristics to be understood are discussed in Sections 4.2.1 and 4.2.2. Table A-20 lists

TABLE A-19

Minimum Data from Treatability Studies

Data Type
Estimated half-lives or specific degradation rate constant(s) for key constituent(s) or classes of waste constituents
Estimated slowest to degrade key constituent of concern and estimated rate or time required for degradation
Toxicity to microbial populations at initial or maximum constituent concentrations
Minimum achievable constituent concentrations
Estimated nutrient application rates
Estimated nutrient maximums and minimums

TABLE A-20

Sampling and Analysis Guidance Documents

Document
"Guide to the Preparation of the Chemical Data Acquisition Plan," ER 1110-1-263 (Chemical Data Quality Management for Hazardous Waste Remedial Activities).
American Society of Agronomy/Soil Science Society of America. 1965. "Methods of Soil Analysis, Parts 1 & 2." Madison, Wisconsin.
American Public Health Association. 1992. *Standard Methods for the Examination of Water and Wastewater American Public Health Association, 18th Edition.*
American Society for Testing and Materials (ASTM). 1995a. "Method for Particle Size Analysis of Soil." *Annual Book of ASTM Standards, Volume 04.08.* ASTM D 422—60 (1990)
American Society for Testing and Materials (ASTM). 1995b. "Test Method for Classification of Soils for Engineering Purposes." *Annual Book of ASTM Standards, Volume 04.08.* ASTM D 2487—90.
American Society for Testing and Materials (ASTM). 1995c. "Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." *Annual Book of ASTM Standards, Volume 04.08.* ASTM D 4318—84.
U.S. Army Corps of Engineers. "USACE Engineering Regulation for Chemical Data Quality Management for Hazardous Waste Remedial Activities," ER1110—1—2 63.
U.S. Environmental Protection Agency. 1986d. *EPA SW-846, Test Methods for the Evaluation of Solid Wastes, Physical/Chemical Methods* (Third Edition).
U.S. Environmental Protection Agency. 1991d. "EPA Contract Laboratory Statement of Work (CLP SOW) for Inorganics (ILM1.8) or Organics (OLM1.8)."
U.S. Environmental Protection Agency. 1983c. *Methods for the Chemical Analysis of Waters and Wastes*. EPA 600/4—74—020 (March 1983) .
U.S. Department of Agriculture Soil Conservation Service. 1992. *Keys to Soil Taxonomy*.

sources of guidance for sampling and analysis procedures for almost all of the soil physical, chemical and biological parameters typically used in characterization.

4.2.1 Physical Characteristics

4.2.1.1 Moisture Content

For landfarming, the water content of soils or wastes is determined as a percentage of the soil weight [typically 5-40% Field Capacity (water holding capacity) in a gravity drained situation (Baker, 1994)]. For estimating Field Capacity, see Table A-20 for guidance sources. For target moisture content ranges and explanation of field capacity, see Section 6.4.1.

4.2.1.2 Grain Size and Plasticity

Grain size and plasticity analyses of a landfarm soil are done to classify soils, determine the soil's suitability for landfarming, and determine the suitability of the sub-soil base for landfarming and as a barrier to waste migration. Soils can be classified by United States Department of Agriculture (USDA, 1992), Unified Soil Classification System (ASTM, 1995b) or other methods. The evaluation of sub-soils is discussed in Section 5.0 - "Design Requirements."

4.2.1.3 Tillability

Tillability relates to the sum of the properties above, which combine to determine whether the soil is easily and economically tillable or "workable" for mixing and aeration. Proper tillability allows easy plowing and disking to break up and loosen the soils, and allows the soils to retain their loft and open pore structure. Tillable soils should maintain their structure after repeated tillings, and retain moisture in adequate but not saturating amounts. The same properties which would be desirable for crop soil will usually be desirable for a landfarm.

4.2.2 Chemical

Characterization includes chemical analyses of the wastes and soils. Analyses include collective and specific analyses. Collective analyses directly or indirectly quantify the total content of a group or category of compounds. Specific analyses identify and quantify specific compounds. Guidance for methods for various collective and specific chemical analyses can be found in Table A-20. All chemical analyses should conform to the requirements of USACE Engineering Regulation for Chemical Data Quality Management for Hazardous Waste Remedial Activities, ER1110-l-263. See Section 5.1.3.3 - Sunlight in regards to the use of a cover to control soil moisture.

4.2.2.1 Collective Analyses

Collective analyses are used to estimate total load or burden of a chemical type or category in the treatment system. Collective analyses include TPH, TOC, HO&G, PO&G, total Kjeldahl nitrogen (TKN), and total organic halides (TOX). These methods have limitations, but are very economical, widely used, and easily performed to on-site to characterize wastes and monitor landfarms. Collective analyses are good initial analyses if the waste's composition is unknown.

4.2.2.2 Specific Analyses

Specific chemical analyses are methods designed to separate and quantify discrete compounds (e.g., benzene, 1,1,1 trichloroethane, or benzo(a)pyrene). These methods are usually more expensive, require more sophisticated techniques, and are used sparingly as verification of degradation of specific constituents of concern.

4.2.3 Biological

Various biological measurements are used for waste and soil characterization. Several common microbial enumeration (APHA, 1992; ASA, 1965), respirometry (Baker, 1994), and toxicity tests (Baker, 1994; Hinchee, 1994b) can be used to assess the effects of toxic substances on numbers of microbes and changes in their metabolic state (Table A-20). These measures are indicators of remediation and also guide the selection and use of noninhibitory landfarm loading rates. Also, respirometry tests can be used to monitor oxygen uptake as an indicator of microbial metabolism in the presence of waste constituents; ATP determinations can be used as indicators of the health and size of the microbial community; and epifluorescence microscope counts of differentially-stained cells can be used to determine the number of viable cells present.

4.2.3.1 Microbial Enumerations

Many methods are available for enumerating microbes in complex mixtures/samples (ASA, 1965; APHA, 1992). All have drawbacks which may make them inappropriate for specific applications. The most common methods used in landfarm applications are:

- dilution plate counts (pour or spread), and

- most probable number (MPN) estimates (liquid or gel).

These methods involve suspension of a known amount of waste/soil into a diluent followed by transfer of a series of known dilutions to inoculate semi-solid (agar) or liquid growth medium. The inoculated medium is incubated for microbial growth. Finally, numbers of colonies on the agar plates are counted or the number of positive tubes are determined and back-calculated to estimate the microbial population in the original sample.

Microbial enumeration for bacteria and fungi does not reflect the total number of microbes present in the sample, since many variables can inhibit their growth on the media used. Such microbial population estimates should never be used to judge the progress or effectiveness of the remediation process. These counts only estimate the numbers of some microbes still present, and thus indicate that the landfarm soil retains microbial life.

Microbial enumerations merely indicate whether landfarm soils or wastes contain a sufficiently sizable population of microbes to have potential degraders present. Large numbers can indicate either low toxicity of the waste and/or adaptation to the toxicity. Microbial populations in contaminated soil typically range from about 106 colony forming units (CFU) per gram (g) of soil to ~ CFU/g soil (Atlas, 1984a); a higher count does not necessarily mean faster or more complete degradation of the waste. Microbial counts only provide a relative indication of the biological status of the landfarm and are most significant for trends. Counts of specific degraders give assurance that some degraders are present, but often the actual compounds being degraded are unknown, so this approach cannot be used.

4.2.3.2 Microbial Toxicity

Toxicity characterization is needed to develop waste/soil loading rates to prevent toxicity to the microbes, and to measure remediation during operation of the landfarm.

Microtox® is a common toxicity test used to assess metabolic toxicity. It is based on the negative correlation between light output from photobacteria and increasing concentrations of toxicant. Significant decreases in this toxicity with time generally correlate with successful remediation. Guidance on the use of Microtox® is provided by Microbics Corp. of Carlsbad, California, ASTM Special Technical Publication 886 (Petros, et al., 1985), and other publications (Matthews, 1986; Kaiser and Ribo, 1988; Ribo and Kaiser, 1987; Baker, 1994).

4.3 BENCH-SCALE TREATABILITY STUDIES

After characterization, laboratory or bench-scale studies are performed. Several guidance documents are available to use in setting up and conducting a treatability study (See Table A-17(USEPA, 1993c; Baker, 1984; Barnhart, 1989; Barth and Bunch, 1979)]. These studies range from jar or shake flask tests to microcosm tray studies and are intended to:

! demonstrate biodegradability of all or most of the major constituents of the wastes, and

! provide guidance for the pilot and/or demonstration treatability study to follow.

Bench tests should not be directly scaled to full-size. Bench-scale treatability studies are usually developed or designed around the characterization data for the site soils and the waste(s) to be treated.

Treatability tests use the same types of analyses as characterization, and use a program of periodic sampling and analysis to evaluate controlling and monitoring parameters. Additional analyses (such as oxygen uptake tests, respirometry or catalase tests) may be done to monitor the active degradation process (Baker, 1994; ASA, 1965).

4.3.1 Flask Screening

Flask studies are soil slurry studies (Baker, 1994; USEPA, 1993c) used to assess the biodegradability of the wastes under optimal conditions of mass transfer, mixing, nutrient availability, and aeration, usually with various combinations of pH, nutrients, waste concentrations, mixing, aeration, and\or inoculum. The successful set of conditions is then used to design tray studies (See Table A-17).

4.3.2 Tray Microcosm

The bench-scale microcosm for a landfarm is a tray study in which the waste/soil matrix is placed to a tillable depth and amended to achieve a desired range in water, nutrients, and pH. The materials are tilled, sampled, and analyzed periodically. Several treatment protocols may also be used in tray studies to determine the soil system's response to different conditions (See Table A-17).

Microcosm studies are designed to simulate the biotreatability of the wastes under a variety of conditions controlled to simulate those expected in the full-scale treatment.

4.4 PILOT-SCALE STUDIES AND DEMONSTRATIONS

Pilot-scale studies or demonstrations (see Table A-17) are the ideal method to test landfarming treatability because they impose the necessity to perform all of the operations associated with full-scale landfarming, including:

- routine collection of air monitoring data (if required by the Site Safety and Health Plan),
- reapplication or treatment of leachate,
- management of precipitation, and
- operational effects of ambient temperature variations.

Ideally, the demonstration would operate for the expected calendar period of full-scale operation.

Pilot or demonstration studies range from small, lined, constructed treatment pads to large, unlined plots using small garden tractors and movable sprinkler systems. These studies may include several small treatment units with operating conditions different in one or more ways, such as the initial loading rates, tilling rates, and nutrient applications.

Scale-up for nutrients, loading rates, water, etc. is typically based on a direct weight or volume ratio of soil in the full-scale tillable zone relative to the test plot tillable volume or weight. For controlling parameters, the target values for the successful demonstration are the same for scale-up (e.g., if ammonia is kept above 10 mg/Kg in the tillable zone soils in the demonstration, that would also be the operating standard in full-scale). There is no maximum scale-up for landfarming generally used since landfarms do not involve complex geometric scale-up such as do chemical process unit reactors. For design purposes, scale-up of data from treatability is usually done from the pilot or demonstration-scale phase.

4.5 DATA COLLECTION AND EVALUATION

Analyses of biodegradability studies involving petroleum wastes will typically focus on collective parameters unless a specific constituent or set of constituents is considered to be of particular concern. For wood treating wastes, an extraction based set of analyses such as benzene-extractable PAH, PCP, or related compounds may be used. In shake flask tests, nutrients are added at the highest reasonable concentrations and monitored only to determine whether nutrients are still available throughout the test. In tray studies, the same parameters are monitored that would be used in full-scale operations:

- moisture (perhaps by galvanometer or appearance),
- pH,
- nutrients (soil test kits for minimums),
- collective parameter(s),
- specific analyses for constituents of concern, and
- temperature (if not held constant in the lab).

The samples will usually be collected and analyzed at a frequency sufficient to develop a rate curve for changes in constituent (collective or specific) concentrations. In addition, data collection frequency should be adequate to assess changes in nutrient consumption and pH, and thereby assist in the estimate of full-scale addition requirements.

The amount and frequency of the data collected is dependent on the sensitivity or "weight" of the interpretation made from the data. In the screening test, the decision to proceed with more testing is based on positive evidence of biodegradability of the waste. The objective is to determine whether biodegradation (statistically significant levels) has occurred, and to rule out strictly physical/chemical processes (e.g., adsorption, sequestration, and volatilization) in the disappearance of the wastes. The evaluations made are whether any change in the concentration of the constituent(s) is statistically significant and whether that statistically valid change can be presumed or demonstrated to be a function of biodegradation rather than other removal mechanisms. It is reassuring to run test permutations in replicate to determine the statistically-valid average concentration from which a statistical analysis can be performed.

Assuming first order kinetics, it is common to skew sample frequency to sample more often during the early stages of a treatability study to track the expected more rapid initial waste degradation.

4.6 DATA ANALYSIS

Data analysis should focus on trends, correlations between various parameters, and simple statistical tests to determine the validity of the data and calculated results.

Simple line graphs can be used to easily monitor the change(s) in constituent(s) and other parameters, collective and/or specific, to establish time-based trends and rates. Regression (best fit) analyses of the data can predict the likely kinetic reaction order(s). Trends, rates, and presumed reaction order can all be used to estimate the time required to achieve a specific concentration goal. Degradation curves should be examined for the presence of asymptotes at unacceptable concentration(s)

Correlation analyses between various controlling and monitoring parameters and degradation should be used to optimize the process and design.

Potential sources of error for data from treatability studies are listed in Table A-21.

Statistics can be used to establish "average" results for design purposes and to assess the reliability of the data gathered. An excellent reference and practical guide to the use of statistics has been authored by J. L. Phillips, Jr. (Phillips, 1988). A more detailed but focussed statistical guide is by Gilbert (Gilbert, 1987). Statistics often call

TABLE A-21

Sources of Data Error

Sources
Selected methods of sampling and analyses
Sampling
Preservation of samples
Processing of samples
Analysis of samples
Processing, calculation and reporting of analytical results
Transcription of results to data bases or spreadsheets for evaluation and manipulation
Interpretation of the results
Misunderstanding of the limitations of the tests and results

into question specific results and data points and can "smooth" or average the variability caused by unknown errors and variations of individual data points, so that the overall trend remains valid. In some cases, statistics can test the validity of data or correlation with other sets. One of the most critical decisions in any data evaluation is whether a data set or point should be considered different from another data set or point. Statistics allows this determination to be done with varying levels of confidence set by the designer, easing decision making.

Simpler is better in analysis of data. The degree of confidence needed is best judged by the purpose of the data. If the data are used to decide whether to proceed to the next treatability phase, the confidence need only be moderate. If the data are critical to the design of an expensive full-scale treatment process, the confidence needs to be very high.

Degradation rates can be determined and used in scale-up design based on the rate constants calculated using assumed first order kinetics. A commonly used first order equation is:

$$\frac{\Delta C}{\Delta t} = -K_s C$$

Where:

ΔC =	the change in concentration during Δt
Δt =	the change in time
c =	the concentration
K_s =	the rate constant for the constituent

One commonly used parameter derived from the rate constant(s) is half-life, the time it takes for half of the initial concentration to degrade. Section 5.4.1 includes a discussion of the equations used for half-life calculations. Note that these half-life constants should not be extrapolated beyond those concentrations tested during the treatability analyses. Problems with extrapolation of this data are discussed further below and in Section 5.4.1.

One form of this half-life equation is:

$$t_{\frac{1}{2}} = \frac{0.693}{K_s}$$

Where:

$t_{1/2}$ = the half life of the constituent(s) in the soil system and

K_s = the first order rate constant for the particular constituent(s)

These equations assume that the rate is first order for substrate concentration. Biological rate constants and half-lives are actually predictive within an upper and lower limit in most cases and should not be freely extrapolated without testing. If the concentration(s) of the constituents being degraded exceed the metabolic capacity of the biomass, the system is saturated and the kinetics become zero order, no longer dependent on the concentration(s). There will always be upper limits (constituent concentration, saturation, toxicity, climate, solubility limits, etc.) for the actual degradation rate. Extrapolating design to higher loadings based on a half-life determined at lower concentrations can lead to process failure. At low concentrations, degradation also may not reach extrapolated rates. If target clean-up concentrations are low, the system may become asymptotic above the clean-up goal.

Moisture content should be based on pilot, demonstration, or even tray study results or best professional judgement or practice. In the absence of specific site data, *The Water Encyclopedia* (Van der Leeden, et al., 1990) includes a simple flow diagram for estimating agricultural water demand which can be applied to landfarming practices also.

Soil pH can be predicted from results of scale-up of treatability studies, soil type and characterization parameters, including percent base saturation and cation exchange capacity. Typical agricultural soil pH amendments such as crushed or powdered limestone and sulfur can be used. Additional information is provided in Section 6.4.3.

Lift thickness is determined by a subjective assessment of the ease of tillage, and may be determined in the pilot or demonstration phase. The depth of the tilled zone can affect degradation rate by limiting infiltration and air exchange. Consequently, if greater than usual tilling depths are anticipated at full-scale, these should be tested in the demonstration.

5.0 DESIGN REQUIREMENTS

5.1 SITE CHARACTERIZATION

Whether investigating possible sites for a new facility or trying to adapt a remedial site for landfarming, site characterization is important in establishing the limits and criteria of the design. Landfarming has been successfully practiced in all the major climatic regions of the United States, Europe, and Canada, under a wide range of hydrogeologic conditions (API, 1984). These data suggest that very few insurmountable site limitations exist. While "ideal" site characteristics are not realistically available, critical site characteristics should be addressed in designing and managing the facility.

Assessing sites proposed as landfarming unit locations involves evaluating the site's physical characteristics as well as socio-geographic factors, including land use. The site characterization's fundamental objectives are to identify:

- potential pathways for contaminant migration (e.g. surface water, groundwater, air emissions, etc.); and

- potential sensitive receptors (those aspects of human health or the environment subject to potential risks in the event of accidental fire, explosion, releases or spills, etc.).

It is the designers' responsibility to determine the applicability of 29 CFR 1910.120 and 29 CFR 1926.65 to the construction and operation of the landfarm project. If applicable, the design shall include health and safety specifications and a Health and Safety Design Analysis (HSDA) as is required by ER-385-l-92. The Corps of Engineers Guide Specification 01110 Safety, Health and Emergency Response (HTRW/UST) shall be used to develop the safety, health and emergency response requirements. Appendix B of ER 385-1-92 shall be used as a guide to develop the health and safety design analysis.

5.1.1 Site Topography and Drainage

The site topography and drainage should be evaluated to determine the:

- drainage and watershed characteristics,
- earthwork necessary to construct the required controls, and
- potential for accidental discharges to surface waters.

Excessively flat slopes can result in ponded water on the site. Ponded water can lead to odor, air emissions or increased groundwater infiltration problems. Grades of 1% are typically sufficient to promote adequate drainage. Shallower grades which avoid standing water are difficult to construct without specialized equipment and surveying techniques.

Slopes steeper than 4% to 6% may require special management practices to minimize erosion potential, such as:

- earthwork to erect berms, diversion ditches, contouring, and terracing; and
- planting and maintaining grass strips.

The cost of such management techniques should be included in site evaluation criteria. Additional design detail on these types of management practices are included in Section 6.4 - "Stormwater and Hydraulic Controls."

5.1.2 Site Geology/Hydrogeology

Characterizing the site's geology and hydrogeology is important in determining potential pathways for contaminant migration and design and monitoring criteria, and consequently the appropriateness of the site for landfarming.

5.1.2.1 Regional Geology

Regional geologic information about the location, its major geologic unit boundaries, and aquifers in state and federal surveys should be correlated with site-specific information derived from on-site test bores. Results from the test bores should be used to develop site maps which illustrate the following:

- depth and characteristics of bedrock;
- stratigraphy and properties of overburden soils;
- rock outcrops;
- aquifer recharge areas; and
- geologic discontinuities (e.g., faults, joints, fissures, sinkholes, etc.).

Emphasis should be placed on delineating the extent of confining and aquifer strata, as they represent the primary retarding and transmissive layers, respectively, for contaminant migration. Outcrops of rock on or near the site may indicate aquifer recharge zones, geologic discontinuities and/or faulting. These features should be investigated to determine their respective impacts on geologic stability and groundwater flow regimes.

The stratigraphy and characteristics of the overburden soils and bedrock will often indicate potential pathways for contaminant migration. These pathways may be used to determine the risks associated within landfarming techniques. For example, a site located within a recharge zone of an aquifer which supplies drinking water may pose an unacceptable risk even if the site is lined prior to applying wastes. Similarly, if a sufficient aquitard exists between the incorporation zone and groundwater sources, cell lining criteria may be established which can reduce the groundwater exposure risks to acceptable levels.

Many states provide specific guidance on geologic siting criteria for landfills. Because of the similar leachate characteristics and production rates, these criteria are often directly applicable to landfarming applications. For example, some states may require that a minimum thickness of clay or other low permeability stratum underlie the treatment area. In lieu of (or in addition to) the low permeability stratum requirement, the state agency may require that the treatment cell be lined with a recompacted clay and/or a synthetic geomembrane liner system.

These additional liner requirements are often based upon waste type classifications established by the state agency. Each waste classification may correspond to specific liner requirements. State agencies should be contacted to determine how specific wastes will be classified. Additional discussion of liner criteria is included in Section 5.6 - "Liners and Leachate Collection Systems."

5.1.2.2 Hydrogeology

Related to the definition of geologic units is the definition and delineation of hydrogeologic processes which occur within the limits of the proposed site. Hydrogeologic information may be obtained from published state and federal geological surveys, state water well records and site-specific data. Important hydrogeologic considerations include:

- depth and extent of water bearing strata,
- potentiometric surfaces of water bearing strata,
- permeability characteristics of confining and transmissive strata,
- depth and extent of drinking water aquifers,
- water quality data for the respective aquifers, and
- vadose zone saturation levels.

From these characteristics, the speed and direction of fluid movement through the soil can be determined. Ideally, the maximum depth of the treatment zone should be located above the seasonally high groundwater table. This will prevent contamination of the groundwater with untreated waste and provide sufficient aeration of the soils to prevent the development of anaerobic conditions. Where liners and leachate collection systems are not installed, the bottom of the treatment zone is typically maintained at least 1 meter above the seasonally high groundwater elevation to provide room to install an unsaturated zone monitoring system.

Shallow or perched water tables often occur in fine-grained soils with low hydraulic conductivities. These shallow water tables may not render the site unacceptable for landfarming since these soils do not typically provide a groundwater resource. Experience at such sites indicates that they can be operated successfully with appropriate waste application scheduling and/or drainage to meet overall performance standards. Wastes should not be applied to saturated soils or locations in which the groundwater elevation is at or near the surface. Application of wastes during these conditions could result in the run-off of excess waste constituents into the stormwater management system and/or the elimination of sufficient interstitial pore space oxygen which is needed to sustain the biological activity. In areas with highly variable groundwater elevations, the application of wastes should be delayed until the groundwater elevation has receded to such an extent that the wastes/soil matrix can be tilled to effectively re-entrain sufficient oxygen to sustain the biological activity. In areas with persistently high groundwater elevations, the treatment area should be intersected with sufficiently deep drainage ditches to effectively lower the groundwater elevation until treatment is completed.

In addition, hydraulic barriers may be installed to prevent inflow and infiltration of groundwater and migration of waste constituents (see Section 5.6 - "Liners and Leachate Collection Systems")

An evaluation of the groundwater flow direction and speed is required to determine the appropriate locations and depths of up-gradient and down-gradient monitoring wells. Up-gradient wells will be required to monitor any changes in background conditions. Down-gradient wells are used to monitor the waste containment within the treatment cell. The wells should be screened within the strata most likely to be impacted by the unit operations.

Additional detail on groundwater monitoring system design can be found in Section 5.6 - "Liners and Leachate Collection Systems."

Current uses of groundwater within the area should be determined. Specific areas may be subject to use restrictions from groundwater quality concerns. These areas typically include the recharge zones of major drinking water aquifers. Water well records should be investigated to determine whether nearby communities are utilizing specific geologic units as a water resource. Experience indicates that even very thin or seemingly insignificant water-bearing strata should be considered as a potential resource for homes or small residential communities.

Some states may require that a minimum distance be maintained between the treatment area and groundwater production wells. Similarly, some states may require that the zone of incorporation be maintained a minimum distance above the seasonal high groundwater elevation.

5.1.2.3 Soils

Since soils are the treatment media for the unit, careful consideration must be given to selecting a site with soil properties suitable for landfarming operations. Soil criteria which impact the treatability of the waste are discussed in more detail in Section 4.0 - "Treatability Studies." Soil criteria which affect waste leachability and subsequent containment design criteria are discussed in further detail in Section 5.6 - "Liners and Leachate Collection Systems." Soil units and horizons located within the extent of the treatment cell should be identified to estimate the potential workability of the soil and the potential for erosion.

A detailed soil survey should be conducted in accordance with the procedures established by the U.S. Department of Agriculture's (USDA) Soil Conservation Service (SCS) (USDA, 1992). Estimates of the boundaries of specific soil series may be obtained from soil survey maps prepared by the SCS. These maps also contain descriptions of each soil unit, which include:

- estimates of soil erodability (used to calculate terrace spacings and other erosion control structures);

- information on subsoil depth and texture (used to estimate whether suitable soil is available for the construction of clay berms or hydraulic barrier layers); and

- measurements of surface texture (used to estimate water retention capacity).

SCS soil surveys may also contain information on average and/or seasonal high groundwater elevations.

Empirical formulas have been developed to estimate the quantity of soil eroded from a site. Excessive erosion may result in:

- contaminant transport from the site;

- degradation of down-stream water quality;

- loss of treatment media; and

- clogging or loss of capacity in stormwater control features.

5.1.2.4 Geotechnical Conditions

In addition to soil properties which impact biological activity and potential contaminant migration pathways, soil strength data and consolidation parameters are required for facilities with significant structures (e.g., dikes, storage tanks, buildings, etc.). A geotechnical investigation should be conducted to determine soil properties related to the structures. This investigation may be easily incorporated with the geologic/hydrogeologic investigation phases.

Geotechnical investigation requirements are dependent on the respective structures to be constructed on the site. Specific attention should be paid to slope stability analyses where large containment dikes are required. Slope failures of containment dikes can have devastating impacts on liner and leachate collection systems. Geotechnical investigation programs should be developed by qualified geotechnical engineers with specific regional experience.

5.1.3 Climate

Although climate greatly influences waste treatment rates, climatic conditions are not typically a major consideration on site selection. Careful design and operation can overcome most climatic conditions. As a result, landfarming sites are typically located at or near the waste generation site to minimize transportation costs.

Because of the significant impacts of climate on the operational management of landfarming units (see Section 6.0 - "Operational Requirements"), it is important to evaluate the anticipated climatic conditions.

5.1.3.1 Precipitation

Precipitation may provide the major component of irrigation water for many landfarming units. The net water balance at a facility is an important consideration. Regions with seasonally wet climates promote anaerobic conditions and may restrict equipment access to the unit. Such regions may require special designs or operational procedures, such as:

- increased temporary waste storage capacity,
- field surface and/or subsurface drainage systems,
- run-off and/or run-on control structures,
- specialized waste handling or tilling equipment with flotation tires, and
- carefully timed waste applications.

Carefully timed waste applications may be applied to sites subject to a long rainy season such as monsoonal rains in tropical locations. At these types of sites, wastes are typically delayed until the end of the rainy season. Similarly, waste application at sites subject to tropical storm threats may be delayed if a tropical storm presents an immediate threat.

Design requirements and details for these control measures are discussed in further detail in Section 5.5 - "Stormwater and Hydraulic Controls."

Daily, monthly and annual rainfall data can be obtained from the National Oceanographic and Atmospheric Administration (NOAA).

This data may be used in conjunction with site-specific drainage and infiltration data to determine the water balance at the site. Mathematical models such as the HELP model (See Section 5.6 - "Liners and Leachate Collection Systems") may be used to estimate any water excesses or make-up requirements. Design storm data used to size conveyances and stormwater storage facilities can be obtained from local sources or the Department of Commerce, Weather Bureau (U.S. Department of Commerce, 1963).

The use of covers such as sheds or warehouses to mitigate against the effects of heavy precipitation may not be beneficial. Sunlight often helps to promote the degradation of the waste compounds. For further information see Section 5.1.3.3.

5.1.3.2 Temperature

Organic waste degradation effectively ceases when soil temperatures remain below 10°C for extended periods. Therefore, units located in northern or mountainous regions may have seasonal treatment restrictions and may require increased storage capacities. When economic or regulatory constraints require treatment even during cold (<10°C) periods, it may be conducted inside heated buildings.

Daily atmospheric temperature data can be obtained from NOAA. Soil temperatures for bare surface soils are commonly greater than ambient atmospheric temperatures by 2.2-5.5°C during daylight hours. Surface soil temperatures at landfarming sites may exceed ambient temperatures by 5.5 to 8.3°C due to increased microbial respiration and the increased radiant energy absorption due to the darker soil color which result from stained or oily wastes.

5.1.3.3 Sunlight

If buildings or roofs must be considered to minimize environmental extremes, the impact of omitting the beneficial effects of ultraviolet radiation in sunlight should be considered because of its significant role in degrading particular wastes (such as PAHs).

5.1.3.4 Evapotranspiration

Evapotranspiration involves two moisture loss processes: direct evaporation and transpiration from plants. Published evapotranspiration rates may overestimate water loss for a site because typical bioremediation landfarms do not include vegetation. Similarly, frequent soil tillage significantly increases direct (pan) evaporation rates. Experience indicates that evapotranspiration rates more accurately predict moisture loss rates for landfarming applications than do pan evaporation rates.

Pan evaporation rates for specific locations can be obtained from NOAA Documents (NOAA, 1976). Evapotranspiration rates may be obtained from local SCS representatives, locally available agricultural resources, or synthetic weather generation models such as WGEN provided in the HELP model (see Section 5.6 - "Liners and Leachate Collection Systems").

5.1.3.5 <u>Prevailing Winds</u>

Although management practices strive to minimize air emissions, atmospheric transport of contaminants may unavoidably occur:

- During hot weather or after recent waste applications due to volatilization of waste constituents;
- When aerosols are generated from spray irrigation with the reapplication of leachate;
- During high wind events when tilled soils are most susceptible to wind erosion;
- During tilling or waste spreading operations when dust is generated; and
- During accidental fires, explosions or releases.

As a result, prevailing wind directions may impact the siting criteria of facilities located near major population centers or sensitive receptors. Methods to control wind dispersal are discussed in further detail in Section 5.8 - "Air Emission Controls."

Wind is a vector quantity, described by both magnitude and direction. Frequency analyses used to determine prevailing winds use a two-way frequency distribution to construct a standard wind rose. An example wind rose is presented in Figure A-3.

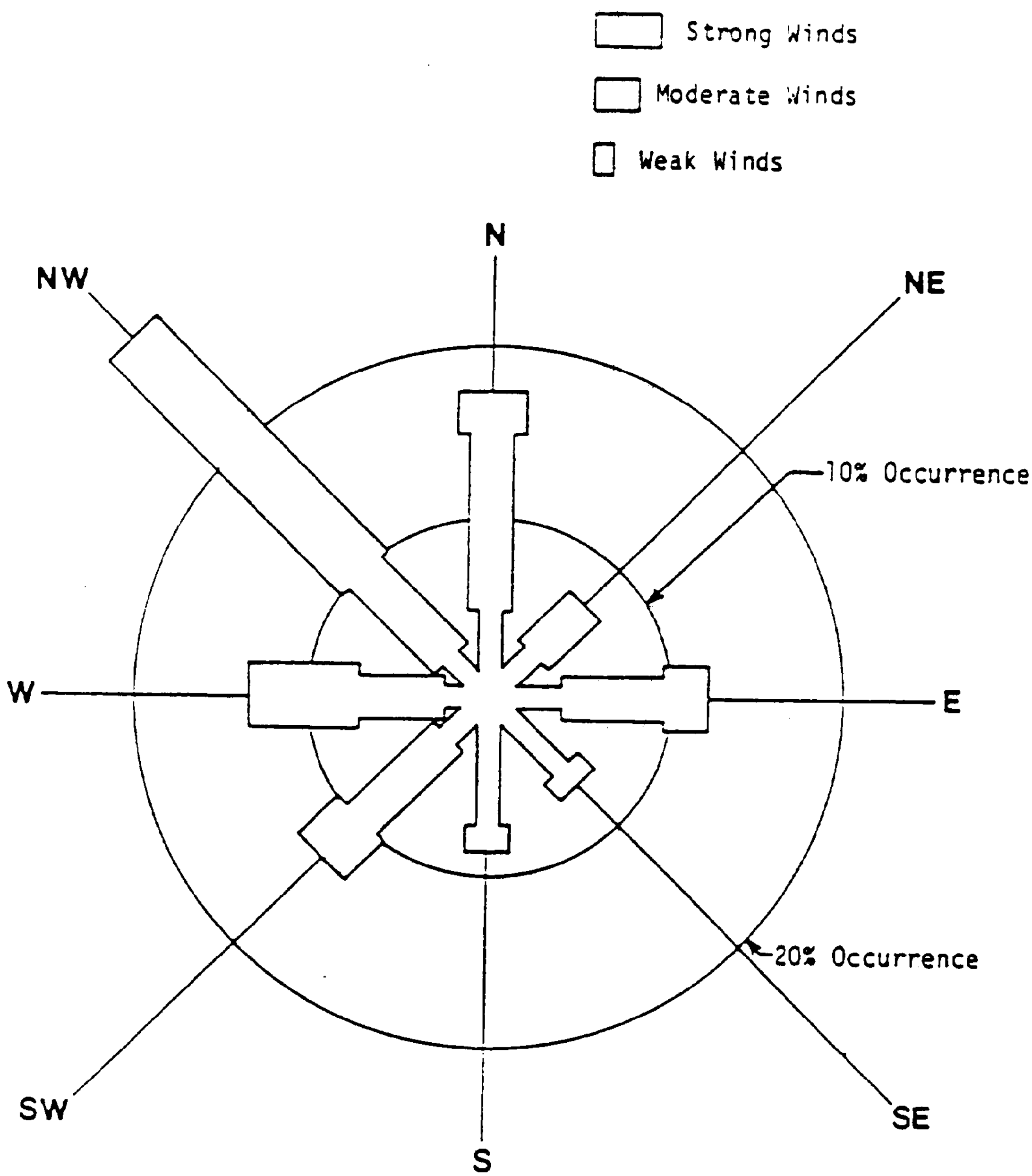


FIGURE A-3
EXAMPLE WIND ROSE

Collection of site-specific meteorological data for atmospheric dispersion modelling should be considered during the pre-design phase if air monitoring of the facility is likely. Meteorological data are available from the EPA's Office of Air Quality Planning and Standards - Technology Transfer Network. Other good sources of meteorological data include local airports and military installations.

5.1.4 Socio-Geographic Impacts

Legal factors which affect facility siting may include:

- zoning restrictions,
- special designated ecological areas (e.g., wetlands, endangered species habitats, recreational areas, etc.),
- historical or archeological sites,
- relocation of residents, and
- impacts on traffic patterns and transportation restrictions and requirements.

Local, state and federal laws governing these considerations will affect site selection. In addition to the legal restraints, social factors which must often be considered include:

- proximity to existing or planned communities, or industrial developments,
- effects on the local economy and property values,
- visual or aesthetic impacts, and
- public acceptance.

Buffer Zones. Buffer zones around treatment facilities may be utilized to provide a separation barrier for the local community and any impacts by nuisance dusts, odors, volatile organic compounds (VOCs) and microbial emissions. During the application of the waste, microorganisms in aerosols or odors may be transported by the wind from the application point to the site's boundaries. Typically, "standard distances" have been established by state guidelines for municipal effluent biosolids and their landfarm application. These distances are primarily concerned with the transport of pathogenic organisms beyond the treatment boundaries. If the wastes do not contain such organisms because of their nature (industrial waste) or pretreatment, then the buffer zones may be reduced.

Buffer zone criteria established by the state agency for landfill applications are often generically applied to landfarming applications. These buffer zones can be found in landfill design criteria guidance documents provided by most state agencies.

Generally, buffer zones range from 5~to 60 meters wide. The buffer zone can be minimized through:

- proper design selection of application systems,

- operational constraints to limit application during unfavorable weather conditions (e.g. high winds or thermal inversions), and

- locating the units to take advantage of uncleared land to serve as a buffer zone.

Public opinion against a site will likely be stronger the less the buffer distance between a proposed site and residences.

Boundaries. A site may be bordered by a variety of areas/features that can influence the attractiveness of a property for landfarming. The following types of areas/features may be detrimental to siting a facility at a particular location:

- natural water features - rivers, wetlands, etc.
- communities - residential and commercial

Natural water features pose a threat to the facility through flooding and high groundwater levels. Regulations and public opinion may be against locating a waste treatment facility near such natural features. The public probably will object to siting a facility near a residential or commercial community.

Roads. Access roads serve as one of the main means of transporting waste to a treatment facility. It is important to have well designed and maintained access roads both inside a facility and from the waste source. Travel time may be decreased if the vehicle operator does not have to worry about the condition of the roads. Design concerns for in-plant roads are site-specific. However, most in-plant roads will consist of flexible pavements (e.g. gravel or asphalt) to provide all-weather service and because of the ease of construction and maintenance.

If hazardous materials are to be transported off site via public roads, rail, waterways or other means, the transporter must comply with the provisions of 40 CFR Part 263, subject to EPA jurisdiction, and 49 CFR Subchapter C, subject to the Department of Transportation jurisdiction. In rural areas, owners or operators may need to consider the potential for damaging local roads as a result of heavy waste transport traffic. Public opinion will likely be against the additional traffic, especially heavy vehicles near residential areas.

5.2 DESIGN SEQUENCE

A landfarm is usually designed in a specific sequence to permit the orderly calculation of the equipment sizes and space needs. While some peripheral equipment sizing can be performed simultaneously, the critical sizing of the treatment cell represents a balance between the available land area, the volume of soil (or sludge) to be treated, and the time required to meet the clean-up goals.

Thus, the area and lift thickness of the treatment cell is initially calculated from an estimate of the time for treatment of the expected volume of waste, based on the degradation rate predicted from the treatability study. Once a treatment depth is selected, the containing walls (usually berms) are sized. From these and a knowledge of area meteorological conditions, the necessary support construction for the cell (liners and water collection), the water control sump and the entrance/exit ramps for equipment can be sized.

Most support systems for landfarming are related to water management. Thus, tanks, pumps and distribution equipment are sized based on the expected water-pumping requirements. Tilling equipment, its requisite decontamination pads, and equipment storage may also be selected once the treatment area, depth and frequency of tilling are calculated. More detailed design procedures are given below. An example design for the landfarming of fuel-contaminated soils is included in Appendix D.

5.3 LANDFARMING OPERATIONAL SCHEMATIC

Figures D-l and D-2 show the plan and profile view of the landfarming system discussed in Appendix D. Additional details for this design example are shown in Figures D-3 and D-4. The water management system is actually the only true process system utilized in most landfarms. Figure D-5 illustrates the process flow diagram for the landfarming system illustrated in Figures D-1 through D-4.

5.4 TREATMENT CELL SIZING

5.4.1 Treatment Duration

The land-limiting constituent (LLC) refers to the compound which requires the longest time to degrade below its proposed target concentration. The LLC can be identified by comparing each waste constituent's initial and final target concentrations to the assimilative capacity of the process for each target constituent. The unit may be sized by dividing the required treatment rate (mass/time) by the assimilative capacity of the unit (mass/time/area) for the LLC.

The rate of degradation of wastes (mass/time) applied in a single application to a landfarming unit varies. Since the biomass degrading the waste decreases as the concentration of the waste in the soil matrix decreases, the rate at which specific constituents degrade decreases with time. As a result, the rate of decay of a specific constituent is most often expressed in terms of its half-life. The concentration of a waste constituent may be estimated at any specific time using the following equation (USEPA, 1983a):

$$C_i = C_o e^{-k_s t_i}$$

where:

C_i = concentration of the waste constituent at time t_1 (mg/Kg of soil)
C_o = initial concentration of the LLC waste constituent (mg/Kg of soil)
k_s = decay rate coefficient of the waste (day^{-1}) as determined in the treatability study
t_i = time to achieve a given concentration (days)

The time required to degrade the waste constituent from an initial concentration to a target concentration may be estimated using the following equation (USEPA, 1983a):

$$t_1 = \frac{1}{k_s} \ln \left| \frac{C_o}{C_i} \right|$$

Care should be taken when initial loading concentrations or target concentrations approach minimum threshold concentrations at which specific constituents have been shown to be treated biologically. At such low concentrations, these formulas may significantly underestimate the time required to achieve the target concentration. <u>These equations should not be used to extrapolate the treatment times and concentrations beyond those tested in the treatability study</u>.

After this first calculation, the design phase uses an iterative process to reach an economical solution. During this phase, the objective is to determine whether it is more economical to use the first calculated LLC area; or to pretreat the waste, removing the LLC and arriving at a new LLC and an associated area. Final unit sizing probably will take several iterations to solve for the most economical operating area, along with the inclusion of the operational properties of the unit.

5.4.2 <u>Treatment Volume</u>

The typical modern landfarm is created to treat:

- a single lift of contaminated soil; or

- repeated applications of contaminated soils which have been impacted by a spill or repeated spills over a prolonged period of time.

In either case, an estimate of the volume of soil requiring containment is made from a site delineation.

The in-situ contaminated soil volume estimate must be multiplied by a "bulking factor" to account for the deliberate loosening of the soil to permit adequate air flow. These bulking factors may range from 1.15 for sandy soils to 1.6 for highly plastic clays. Typical values range from 1.2 to 1.4. These factors are based on field experience with local soils.

5.4.3 Treatment Area

Landfarming usually utilizes a large surface area. Treatment operations are often constrained by both the available surface area and the practical tillage depth. The initial area estimate is usually calculated by assuming a lift thickness.

Lift thicknesses are typically limited by the depth to which the available equipment can till or mix. The upper bound of the initial lift thickness estimate may be either:

- 45 cm (18 in) where the expected treatment cell is greater than 20 by 20 meters (the minimum area required for a standard tractor and disc set); or
- 20 to 30 cm (8 to 12 in) for smaller areas where roto-tillers could be used for tillage.

Where sufficient surface area is available, lift thicknesses in the range of 20-30 cm (8-12 inches) are the most efficient and yield the fastest treatment rates with minimal difficulty. The use of deeper lifts generally causes reduced oxygen diffusion into the lower portion of the lift, reducing the treatment rate. As a result, tilling frequency must be increased to maintain sufficient oxygen levels and treatment efficiencies. This increased tilling frequency increases treatment costs and may potentially damage the soil structure. Damaged soils may require the addition of bulking agents which will also increase treatment costs.

Available space must be evaluated to determine whether sufficient room exists for treatment cells and associated operations; typical non-treatment cell area requirements are 15-25% of total available area. Where ample space is available, square treatment units will reduce capital costs by minimizing the length of the perimeter dikes. However, a minimum length of 20 to 30 meters is preferable for operations which intend to use standard tractor and disc sets to minimize equipment turn around.

Where insufficient area is available to treat the volume of waste in one lift, multiple lifts may be applied to a treatment cell. This will require removing the initial lift prior to the application of a subsequent lift or providing sufficient freeboard to place several lifts atop one another.

Care should be taken when designing landfarming systems where subsequent lifts are stacked. Common problems include:

- Treated soils in lower lifts may be recontaminated by leachate generated by newly applied lifts, and these zones may not be "retreated" because they are below the effective treatment zone; and

- Moisture added to coarse-grained soils may quickly percolate into underlying layers, depriving the treatment zone of needed moisture.

When free draining, course-grained soils (clean sands and gravels) are to be land treated, provisions should be made to either provide more frequent irrigation or minimize the lift thickness and leachate removal system in order to account for the more rapid percolation of the water through the soil media. Additionally, bulking agents may be used to improve the field capacity of these soils.

5.5 STORMWATER AND HYDRAULIC CONTROLS

Stormwater and hydraulic controls consist of those measures required to (a) prevent stormwater run-on, (b) retain contact stormwater and leachate, and (c) minimize the erosion of contaminated soils. Stormwater control and handling methodologies for landfarming units have classically been similar to those used by other civil/agricultural projects and include:

- Perimeter and interior dikes;
- Channels, ditches, swales and culverts;
- Terraces, benches and berms;
- Earthen basins and/or tankage; and
- Sumps, pumps and conveyance piping.

Sizing of the conveyance and storage facilities requires establishing return intervals for design storms to compute peak intensities and quantities, respectively.

5.5.1 Design Storm Criteria

During development of design criteria, the return interval of the design storm (e.g., 25-year, 100-year) should be selected for the purpose of sizing of conveyances and storage facilities. The 25-year storm is most commonly used for sizing hydraulic controls (conveyances and storage) within landfarming units. Where treatment units may be located within flood-prone areas, additional controls (such as perimeter dikes) may be required to prevent flood water run-on. The 100-year storm is most commonly used for sizing run-on control dikes. Design storm return intervals may either be established by regulatory requirements or by comparing the potential cost of damage or accidental release with the cost of control measures and evaluating the associated risks.

5.5.2 Dike Sizing Considerations

Landfarming units utilize dike structures for:

- preventing stormwater run-on,
- segregating treatment cells, and
- preventing stormwater run-off in the event actual conditions exceed design conditions.

In flood-prone areas, perimeter dikes should be sized to prevent flood water run-on and overtopping as a result of current or wave run-up. Freeboard may vary from 0.15 to 0.60 meters (0.5 to 2 ft), depending upon local requirements. A minimum of 0.3

meters (1 ft) of internal freeboard is recommended to prevent spillage of soil during tillage.

The perimeter dike system should not be used to contain stormwater, except in emergencies when actual conditions exceed the design storm conditions. This practice leads to flooding of treatment cells and the development of anaerobic conditions. Instead, internal ditches are typically used to convey stormwater to a collection sump or basin. In the event that actual conditions exceed design assumptions, perimeter dikes may be used to retain water beyond the capacity of the storage facilities to minimize the risk of uncontrolled discharges.

Internal dikes typically consist of small berms used to (a) segregate treatment cells, (b) facilitate irrigation management, and (c) provide personnel and equipment access. These berms can be constructed with standard farm implements and may be added, relocated or removed as operations dictate.

5.5.3 Contact Stormwater and Leachate Storage Considerations

Both contact stormwater and leachate produced from facilities handling RCRA hazardous wastes must be treated as hazardous, regardless of the characteristics of the water. Leachate produced from either RCRA-exempt or non-hazardous facilities should be carefully evaluated. It may potentially be regulated beyond the soil waste classification, since it may contain higher concentrations of waste constituents than contact storm runoff due to its intimate contact with the waste. As a result, determination of the waters' classification (hazardous vs. non-hazardous) has a significant impact on the design of conveyances and storage procedures.

It may be necessary to collect and store leachate in a separate containment facility. Leachate produced from listed hazardous wastes must often be handled as a hazardous waste, while contact stormwater often does not exhibit hazardous characteristics. During bench and pilot-scale testing, leachate which is not specifically listed as hazardous should be tested to determine whether it contains potentially hazardous constituents. Handling of RCRA hazardous leachate often includes additional controls, such as double containment, which can impact space requirements. When leachates are determined to be non-hazardous, they are typically combined with the contact stormwater to minimize the quantity of stormwater handling equipment.

At a minimum, storage facilities should be designed to contain the expected run-off from the design storm at any given time. One approach is to design the capacity for the run-off expected and to maintain the storage facility in an empty condition. Another approach is to provide containment of run-off from previous storms as well as the run-off from the design storm. It is advantageous to use the collected water to irrigate the landfarm. Because the storage facilities cannot be emptied instantaneously, some accumulated water must be included in the design of storage facilities.

5.5.3.1 Designing for Peak Stormwater Run-off

The Rational Method may be used for estimating the volume and rate of run-off generated for a particular design storm. The formula and run-off coefficients for the Rational Method can be found in most civil and hydrology texts.

When selecting Rational Method coefficients, antecedent moisture conditions should be considered. Often design storms occur during a "wet" season, when soil conditions are already near saturation. Through irrigation and/or reapplication of wastes, most landfarms are maintained in a moist condition with water contents well above typical croplands. Many conservative designers assume completely saturated conditions (c=l).

This method is applicable for relatively small areas (<200 acres) in which rainfall is relatively uniform over the entire area and is adequate for most landfarm applications. For very large operable units, Soil Conservation Service (SCS) Curve Number methods may be more appropriate. Large, complex sites may require more sophisticated techniques which calculate the run-off hydrograph and integrate the hydrograph to determine the ultimate volume.

5.5.3.2 Designing for Normal Seasonal Run-off

Rather than treating leachate and contact stormwater, it is often more economical to utilize it for irrigation. This requires sufficient storage to retain surplus water in excess of the design storm previously discussed.

Typically, water balances and long-term storage requirements for stormwater are computed using hydrologic models. One such readily available hydrologic model is the *Hydrologic Evaluation of Landfill Performance (HELP) Model,* (USEPA, 1994b) prepared by the USACE Waterways Experiment Station. Although specifically written to evaluate landfill liner performance in terms of leachate generation rates, this model is readily applicable to landfarming design. The model accepts climatological, soil, and design data and utilizes a solution technique that accounts for the effects of surface storage, runoff, infiltration, percolation, evapotranspiration, soil moisture storage, and lateral drainage.

5.5.3.3 Design of Stormwater Conveyances

Ditches and berms are used to intercept, divert and transport stormwater runoff, while culverts are used to transport water between ditches and impoundments. The first step in sizing ditches is determining the amount of flow which occurs for a particular section of the ditch. Based on the site size and conditions, one of the following methods may be used to determine peak flows on and around the facility being designed:

- Rational Method,
- SCS Small Watershed Method, and
- Computer Models (e.g. HEC 1).

Theoretically, the SCS method may represent the best stormwater runoff model for a landfarming unit because it was developed for agricultural runoff with consideration for soil infiltration characteristics. However, the basic unit of the runoff area is square miles, which is better suited for large agricultural units. Experience indicates that the Rational Method is an adequate method because it is relatively easy to apply to the relatively small land areas of landfarming facilities.

Because landfarminq facilities are subject to erosion, sediments tend to accumulate in the stormwater conveyances and storage facilities. Clean-outs should be provided such that these sediments may be periodically removed and reapplied to the treatment cell.

5.5.3.4 Irrigation Water Controls and Collection

The irrigation system and associated treatment unit should be designed and operated such that no runoff occurs during the application of irrigation water. The easiest means of meeting this constraint is to not exceed the infiltration-percolation capacity of the soil with the application of water. The moisture content of the soil can be used as a gauge for application. To gauge the degree of saturation, the saturation moisture content should be established prior to any waste application.

If the landfarm is treating VOCs, water treatment may be required before the water is reused (sprinkled), to remove the VOCs so that they are not released into the air during sprinkling. Although not commonly required, activated carbon canisters may be used for this purpose. Carbon canisters should be sized such that 10 kilograms of carbon are used for each kilogram of VOC to be removed. Detailed isotherms for specific compounds may be used to refine this estimate of carbon consumption. This data is typically available from carbon suppliers for each type of available carbon.

5.5.4 Erosion Control Considerations

One goal of landfarming unit design is to minimize erosion, thereby minimizing contaminated sediment transport from the facility. Though local criteria vary, it is generally desirable to maintain erosion levels below 2 tons/acre/year. The Universal Soil Loss Equation may be used to estimate the quantity of soil eroded from a particular site. This equation and estimates for its parameters may be found in most agronomy and soil taxonomy texts. Newer models include WEPP & RUSSLT (USDA, 1992).

If the estimates exceed tolerable levels of erosion, benching or terracing may be required. The original type of bench terrace is designed for slopes of up to 25% to 30% and resembles a giant stairway. Modern conservation bench terraces are adapted to slopes of 6% to 8% and aid in moisture retention as well as erosion control. Broadbase terraces are adapted for slopes of approximately 2% and consist of a water-conducting channel and ridge. Contour levees may be used for slopes of less than 2%. Schematics of these types of slopes are illustrated in Figure A-4. The general placement of terraces is across the slope with a slight grade toward one or both ends. Collected water then drains into a culvert or protected waterway, which may be vegetated, covered with stabilization fabrics or rip-rap, and/or impeded (e.g., with silt fences).

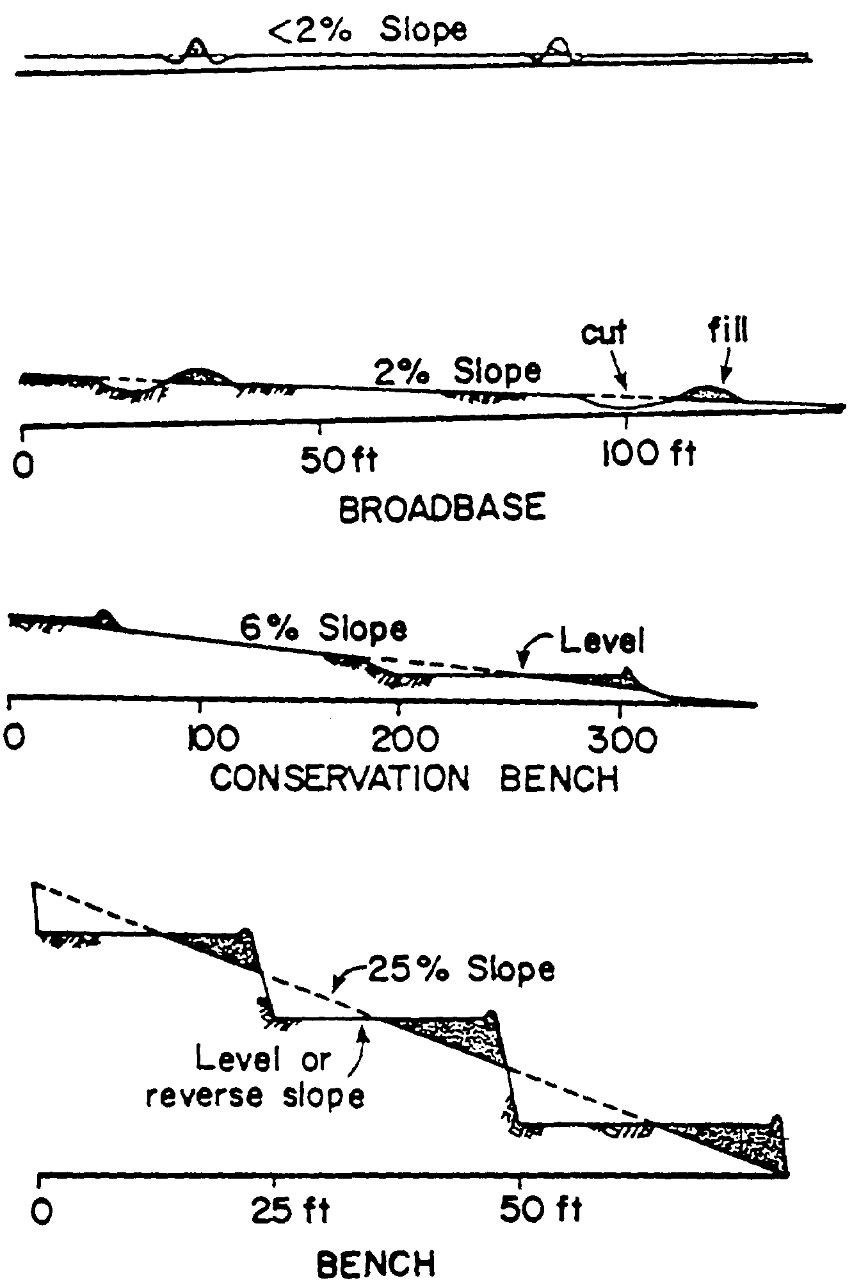


FIGURE A-4

SCHEMATIC DIAGRAM OF GENERAL TYPES OF TERRACES

The vertical interval of the terraces may be roughly estimated as:

$$VI = aS + B$$

Where:

VI =	vertical interval of the terraces (feet)
a =	geographic constant (Figure A-5)
b =	Soil erodibility and cover condition constant (Figure A-6)
S =	Land slope in percent

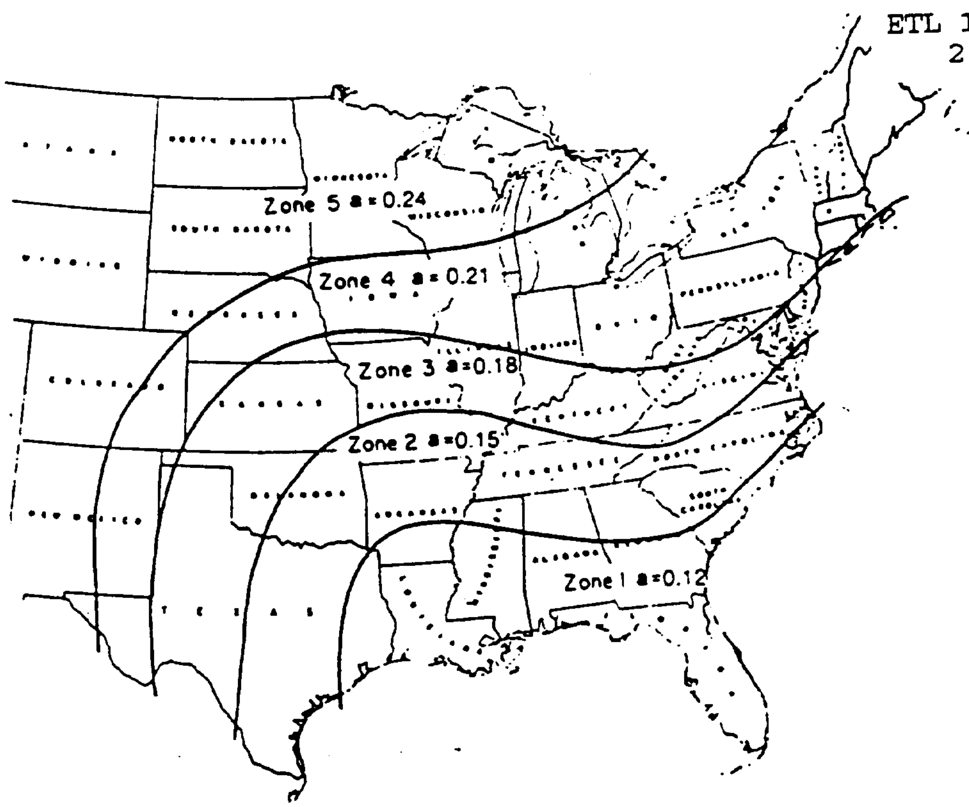
To minimize erosion of sediments in earthen channels, the suggested maximum velocities in Table A-22 should not be exceeded for design conditions.

5.6 LINERS AND LEACHATE COLLECTION SYSTEMS

Facilities which strictly prohibit the incorporation of wastes containing mobile constituents (e.g., RCRA facilities) do not require liners because harmful leachate is eliminated or minimized through careful selection of waste type. The number of these facilities is very limited, since most wastes contain metals or mobile organic constituents which are slow to degrade in comparison with the potential migration rate.

Treatment units which may contain or incorporate mobile and/or non-degradable constituents which may be detrimental to human health or the environment (e.g., corrective actions or RCRA exempted wastes) should be constructed with controls designed to prevent or minimize migration of these constituents from the treatment unit. These controls may consist of:

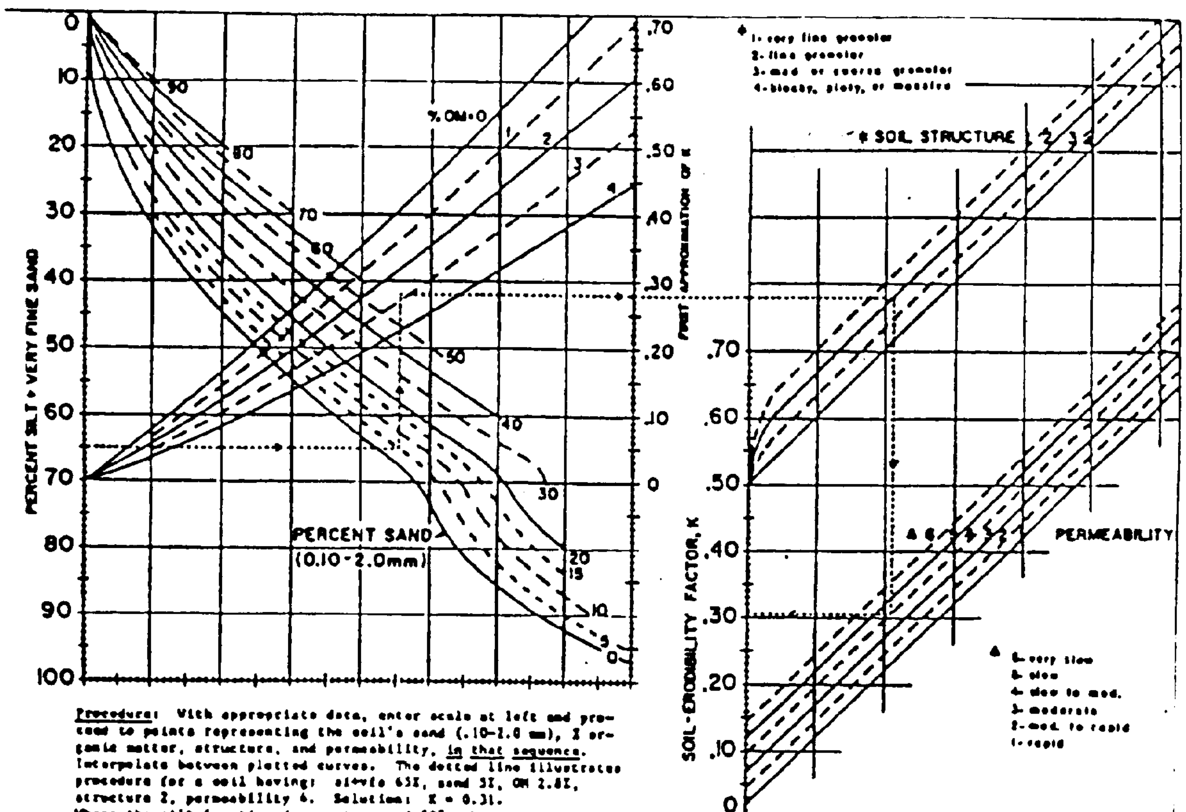
- stormwater collection and storage systems,
- leachate collection systems,
- hydraulic barrier layers, and/or
- leak detection systems.



Values of a and b* in terrace spacing equation, VI = aS + b (ASAE, Terracing Committee, 1980). Reprinted by permission of ASAE.
*Values for b vary and are influenced by soil erodibility, cropping systems, and management systems; in all zones, b will have a value of 0.3, 0.6, 0.9 or 1.2. The low value is applicable to very erodible soils with conventional tillage and little crop residue; the high value is applicable to erosion resistant soils where no-tillage methods are used and a large amount of crop residue remains on the soil surface.

FIGURE A-5

GEOGRAPHIC CONSTANTS FOR TERRACE DESIGN



Procedure: With appropriate data, enter scale at left and proceed to points representing the soil's sand (.10-2.0 mm), % organic matter, structure, and permeability, in that sequence. Interpolate between plotted curves. The dotted line illustrates procedure for a soil having: si+vfs 65%, sand 5%, OM 2.8%, structure 2, permeability 4. Solution: K = 0.31.

Where the silt fraction does not exceed 70%, the equation is $100\ K = 2.1\ M^{1.14}\ (10^{-4})\ (12 - a) + 3.25\ (b - 2) + 2.5\ (c - 3)$ where M = (percent si + vfs) (100 - percent c), a = percent organic matter b = structure code, and c = profile permeability class.

(ASAE, Terracing Committee, 1980 - Reprinted by permission of ASAE)

FIGURE A-6
SOIL ERODIBILITY FACTOR

TABLE A-22

Suggested Maximum Channel Velocities

Soil type or lining (earth: no vegetation)	Maximum Permissible Velocities (fps)		
	Clear Water	Water Carrying fine silts	Water Carrying Sand and Gravel
Fine sand (noncolloidal)	1.5	2.5	1.5
Sandy Loam (noncolloidal)	1.7	2.5	2.0
Silt Loam (noncolloidal)	2.0	3.0	2.0
Ordinary firm loam	2.5	3.5	2.2
Volcanic ash	2.5	3.5	2.0
Fine gravel	2.5	5.0	3.7
Stiff clay (very colloidal)	3.7	5.0	3.0
Graded, loam to cobbles (noncolloidal	3.7	5.0	5.0
Graded, silt to cobbles (colloidal	4.0	5.5	5.0
Alluvial silts (noncolloidal)	2.0	3.5	2.0
Alluvial silts (colloidal	3.7	5.0	3.0
Coarse gravel (noncolloidal	4.0	6.0	6.5
Cobbles and shingles	5.0	5.5	6.5
Shales and hard pans	6.0	6.0	5.0
Van der Leeden, et. al. 1990)			

Constituent migration into the groundwater provides a primary transport mechanism for waste constituents. Mobile, non-degradable constituents within the waste may be prevented from migrating from the treatment cell through a combination of leachate collection systems and hydraulic barrier layers. Leak detection systems may be required for hazardous waste sites where additional assurances of groundwater protection are required.

As discussed in Section 3.0 - "Regulatory Requirements," liner design criteria may be established through use of state design guidance documents or by applying risk assessment criteria. Determination of liner criteria using risk assessment techniques requires that leachate quantities and constituent concentrations be established for sensitive receptors. Estimation of leachate quantities and contaminant fate and transport mechanisms can be computed using the following models:

- *Hydrologic Evaluation of Landfill Performance(HELP Model)* (USEPA, 1994b)

- *Multimedia Exposure Assessment (MULTIMED) Model,* (Sharp-Hansen, et al., 1990)

Specific guidance for design and construction of leachate collection systems and liner systems is beyond the scope of this document. However, considerations specific to the design and construction of landfarming units are discussed in the following sections. More detailed guidance on the design of leachate collection and liner systems can be found in the following EPA design guidance documents:

- *Design and Construction of RCRA/CERCLA Final Covers,* (USEPA, 1991b)

- *Geosynthetic Design Guidance for Landfill Cells and Surface Impoundments,* (USEPA, 1989c)

- *EPA Guide to Technical Resources for the Design of Land Disposal Facilities,* (USEPA, 1988a)

- *Quality Assurance and Quality Control for Waste Containment Facilities,* (USEPA, 1993e)

- Requirements for Hazardous Waste Landfill Design, Construction and Closure (EPA/625/4-89/022)

The following guide specifications for military construction are also available:

- CEGS No. 02243 - Drainage Layer
- CEGS No. 02271 - Waste Containment Geomembrane
- CEGS No. 02272 - Separation/Filtration Geotextile
- CEGS No. 02273 - Geonet
- CEGS No. 02442 - Geosynthetic Clay Liner
- CEGS No. 02443 - Low Permeability Clay Layer

5.6.1 Leachate Controls and Collection

A major means of controlling leachate migration from the treatment cell entails minimizing the head of water on the unit area and controlling application of the waste. Increased hydraulic heads above the liner result in increased leachate migration rates through the liner or defects in the liner. This hydraulic head may be minimized by sloping the site to remove standing water, and by installing an underdrain system (leachate collection system) below the treatment zone to remove excess water and/or liquid waste.

The lateral drainage layer transports leachate from the treatment zone to collection piping and subsequently to a sump. Landfill applications have typically used coarse granular fills, geotextiles and geosynthetic drainage nets to form leachate collection layers. These applications have utilized non-woven geotextiles to maintain separation between waste packs and sand, gravel and/or drainage net layers.

Many leachate collection configurations typical for landfills should not be used for landfarming applications. Some problems unique to landfarming applications are:

- Non-woven geotextiles form an excellent substrate for biological activity. Because of the promoted biological environment, these materials tend to clog relatively quickly. Their use should, therefore, be avoided where possible.

- Applying and removing lifts of contaminated material can damage liners and drainage layers when exposed to equipment traffic. Therefore, synthetic drainage nets should not be used in place of coarse granular soils for leachate collection systems. Drainage nets may, however, be used in leak detection layers.

- Removing lifts of contaminated material requires scraping the treated lift from the treatment cell, typically with a front-end loader or mechanical pan. To protect the leachate collection and liner layers, an armoring layer (gravel or crushed stone) is required to indicate over-excavation to equipment operator. This armoring layer is typically incorporated into the leachate collection layer.

- Because landfarms are inherently shallow, buried gravel-packed sumps typical to landfills may not be required. Leachate collection headers may be routed directly to open sumps, which may be constructed of reinforced concrete, vertical caisson pipes of varying' materials, lined earthen construction, etc. Sumps which remain unpacked increase the sumps' volume, and subsequently reduce pump cycling, capital, and operation and maintenance costs.

The thicknesses and transmissivities of the leachate collection layer may be sized based on state guidance or after estimates of leachate production rates are calculated. The HELP model contains techniques for estimating leachate production and transmission rates for alternative designs.

The following are additional design considerations for landfarming leachate collection systems:

- The granular layer should be <u>at least</u> 0.30 meters thick or, as a rule of thumb, at least half the thickness of the tilling depth to minimize damage to the underlying layers.

- The granular layer should be inspected and repaired after each lift removal operation.

- The granular layers should primarily consist of well-compacted, well-graded crushed stones or gravels with minimum compacted permeabilities between 10^{-2} cm/s and 10^{-3} cm/s (28 to 2.8 ft/day). Landfill leachate collection layers typically consist of poorly graded sands and gravels placed with little compaction efforts to maximize permeability. Sands offer little resistance to tilling and excavation equipment. Poorly graded and loosely compacted materials are also easier to excavate than well-graded, dense materials.

- Because of promoted biological activity, geotextiles should be omitted where practical to avoid clogging. This requires that dramatic changes in grain size at layer interfaces be avoided. For example, silty or clayey soils should not be placed directly upon a gravel layer which contains few fines. The overlying soil would rapidly "sift" into the gravel layer, effectively clogging the gravel layer. Alternatively, the gravel layer should either be overlain by, or mixed with, a medium- to fine-sand which will prevent the overlying layer from clogging the gravel. Sizing of boundary soils may be performed similarly to the sizing of sand/gravel packs for well construction and may be computed using the procedures in the EPA's *Manual of Water Well Construction Practices* (USEPA, 1975).

- Because of the reduced permeability of well-graded, dense fills and the propensity of the armoring/leachate collection layer to clog, an additional (more permeable) layer may be required to laterally transmit the leachate to the collection piping system.

- Since geotextiles must be avoided, drainage collection laterals (pipes) should be slotted instead of perforated. Perforated pipes tend to allow more fines to infiltrate into and clog the collection system. The slots should be appropriately sized for the surrounding gravel pack per EPA's *Manual of Water Well Construction Practices* (USEPA, 1975).

- Sumps which collect hazardous constituents may require double containment. Sumps which collect leachate containing non-methane VOCs may require a cover and venting through carbon.

5.6.2 Liners / Hydraulic Barriers

Hydraulic barriers protect existing soils and aquifers by retarding the vertical and lateral migration of wastes and leachate from wastes. For many years, several different types of hydraulic barriers have been successfully used in landfarms, landfills, impoundments and closures. These include:

- recompacted clay liners,
- geosynthetic clay liners, and
- geomembrane liners.

Determination of lining requirements should be made in accordance with Section 3.0 - "Regulatory Requirements." A more detailed discussion of the advantages and disadvantages of various liner materials is included in Section 8.0 - "Materials of Construction." Details of construction for liners can be found in the references listed previously in this section.

5.6.3 Leak Detection Systems

Leak detection systems for hazardous waste landfarming units are not significantly different than those utilized for landfill designs. These systems may be constructed with granular soils and/or geosynthetic layers in accordance with the reference guidance documents cited for liner construction.

5.7 SUPPORT FACILITIES

5.7.1 Tillage Equipment

Tillage equipment is sized to maximize the productivity of operating personnel. This typically translates into equipment which can till the entire treatment area in approximately 1 day. Since farm machinery is typically modular in size, the size which achieves the tillage objectives with a single unit is used.

For contaminated soil landfarms, the usual equipment, tractor and disc harrow, is available from farm equipment suppliers in new or used condition. Typical disc set ranges from 2 to 5 meters (6 to 16 feet) in width and 45 cm (18 in) in disc height. The degree of difficulty in pulling the discs through the soil determines the required horsepower for the tractor. Local equipment suppliers can assist with determining the tractor sizes. For initial estimates, a 2-meter-wide disc harrow tilling 20 cm deep typically requires a 30- to 35-HP tractor; this equipment can till several acres per day.

Although tractor and disc harrows are the most common mixing equipment used, roto-tillers, pulvamixers and chisel plows may be used for specialized applications. Roto-tillers are particularly useful in small or constrained treatment cells where larger equipment cannot maneuver. Various types of rototillers offer much better mixing than the disc harrows, increasing the uniformity of contaminant distribution and access of microorganisms to the contaminant. Tractor-mounted rototillers can be obtained in most sizes required for the efficient coverage of various sizes of land treatment units.

Pulvamixers are particularly useful when either air emissions must be controlled during mixing or high energies are required for mixing (particularly in wet, highly plastic clays). Use of pulvamixers should not be excessive to avoid damage to the soil structure. Chisel plows have been used where very thick lifts are to be mixed (particularly in cohesionless soils). Chisel plows should be avoided in cohesive soils since they tend to "roll over" the soil mass without entraining a significant amount of "fresh" air.

5.7.2 Pumps

The sump pump is sized to keep the sump water below the float switch level during a storm event. The pump which transfers water from the storage tank to the landfarm is sized to provide the equivalent of 2 cm of water per day over the entire area of the landfarm. To ensure that the sprinklers will function properly, the pressure drop through the distribution system (usually hoses and sprinklers) must be accounted for.

5.7.3 Water Distribution Systems

Water is usually distributed across the surface of the landfarm using soaker hoses or lawn sprinklers that are readily available, inexpensive and reliable. Covered landfarms are more readily served by soaker hoses because the evaporation rate is lower and the cover is only removed for tillage. For open landfarms, hoses and sprinklers are used to cover the surface as evenly as possible. Further details on designing water distribution systems can be found in EPA's guidance document (USEPA, 1993b).

5.7.4 Decontamination Areas

Equipment and personnel may transport contaminants away from a landfarming facility. A variety of activities may put equipment and personnel into contact with the waste. The following are examples:

! waste excavation,
! waste transportation,
! waste application and tillage, and
! site monitoring.

Site design should include decontamination facilities for both equipment and personnel. Equipment decontamination areas should be designed for the largest piece of equipment, and should be located close to the waste to minimize the impact of contaminant transport. The following items should be included for an equipment decontamination station:

! potable water source,

! power source to operate steam generators and high-pressure water pumps,

! pump capable of minimum 0.2 L/s flow at 6900 kPa discharge pressure with internal relief valves or safety shutoff,

! portable water heater capable of providing 0.2 L/s of flow at 55°C or 0.2 L/s steam (0.2 quality) at 160°C,

- high-pressure water hoses constructed with reinforcing fabric suitable for continuous service at 180°C and a safe working pressure of at least twice the maximum discharge pressure of the water/steam heating equipment,

- a sealed pad with drains and walls to contain spray and splash usually constructed of reinforced concrete;

- sump to collect wash water from the pad or drainage control channelling which directs wash water into stormwater or leachate sumps (depending upon regulatory requirements), and

- designated decontamination and exclusion zones for personnel working at the decontamination stations.

Decontamination facilities for personnel may be incorporated with the equipment facilities. These facilities are not as extensive as equipment decontamination stations. Portable showers, wash buckets with detergents and scrub brushes are a few examples of decontamination equipment required for personnel.

5.7.5 Storage Areas

An area may need to be allocated for the temporary storage of wastes prior to their treatment at the landfarm. Sizing is based on waste soil generation or excavation rates versus treatment rates.

An area needs to be allocated for the assembly, maintenance and storage of equipment and materials related to treatment operations during sizing of the landfarm. The size of the area will vary depending on the facility's size and the types of equipment utilized. The area may include the following items:

- small storage tanks used for nutrient storage, leachate storage, etc.;

- equipment maintenance shop;

- piping materials and assembly, etc.; and

- temporary handling of roll-off or shipping containers.

5.8 AIR EMISSION CONTROLS

Two types of air emissions must be considered in design of controls for landfarming facility:

- volatile organic emissions from the waste, and
- dust control.

Controls must be designed to minimize the effect on personnel operating the facility, as well as personnel in the adjacent area.

5.8.1 Volatile Organic Emissions

The design for air emissions from volatile organics (where required) needs to include:

- review of the waste to be applied and a determination whether the potential exists for volatile organic emissions; and

- if the potential exists, a plan to provide personnel monitoring as well as fence line monitoring.

The plan must specify all protective equipment required to minimize risk of exposure to landfarm staff. Personnel monitoring badges may be useful or required.

Typically, monitoring is performed across the cell and at the fence line using a photoionization detector (PID) calibrated to an appropriate standard gas. The threshold reading for ceasing operations is specified in the site Health and Safety Plan.

5.8.2 Dust Control

Procedures must be established to minimize dust emission, potentially to below some regulatory limit (depending on the nature and existence of an air discharge permit). These controls could include:

- suspension of activities during high wind periods,
- covering the landfarm with a plastic liner, and
- application of water over the treatment zone.

Dust emissions are of particular concern where the wastes may contain toxic metals or semivolatile constituents which when adsorbed or attached to the dust particles may migrate from the treatment unit. For these sites, suppression of dust may be required at levels well below those established for "nuisance" dust.

5.8.3 Air Pathway Analysis

Depending upon the toxicity of the waste constituents and local regulatory requirements, an air pathway analysis may be required to determine constituent emissions levels during landfarm operation and construction. These analyses results may be used to determine the need for control technologies and air monitoring requirements.

The designer should use ETL 0375 "Air Pathway Analysis for the Design of Hazardous, Toxic and Radioactive Waste (HTRW) Remedial Action Projects" as a guide for performing these analyses.

5.9 SECURITY

Security at a landfarming site is concerned with the safety of system equipment and facilities as well as safety of unauthorized personnel who may come in contact with the site. Different levels of security are dependent upon the proximity of the site to populated areas and any special problems related to the waste.

At a minimum, sites containing hazardous materials are typically enclosed within a 2-meter (6 foot) chain-link fence topped with three stands of barbed wire. Entrance and egress control is provided by either administrative personnel or full-time security personnel. Depending on the topography and vegetation on the site and adjoining areas, entrance gates may suffice to prevent unauthorized vehicular access.

Operations within the treatment unit are typically restricted to daylight hours. Therefore, supplemental lighting of the treatment area is typically unnecessary.

5.10 UTILITIES

Larger landfarming facilities and continuous treatment units will usually have electrical, water, communication, and sanitary services. Remote sites may have to extend existing service or use acceptable substitutes. Portable chemical toilets can be used to avoid the high cost of extending sewer lines; potable water may be trucked in; and an electric generator may be used instead of having power lines run into the site. Some large hazardous waste treatment units have used gasoline-powered pumps to provide sprinkling and decontamination water, a tractor and discs for tilling, and a portable toilet.

Water should be available for:

- drinking,
- dust control,
- decontamination and equipment washing,
- irrigation, and
- employee sanitary facilities.

Telephone or radio communications may be necessary to call for emergency assistance.

6.0 OPERATION REQUIREMENTS

Previous chapters have discussed the general principles of landfarm design and operation. This chapter will describes the operating requirements for successful waste remediation.

6.1 SAFETY

For landfarming operations, the operating contractor should write a site safety and health plan that meets the requirements of the safety, health and emergency response specifications. If the operating contractor adheres to the specifications, his operation will be in compliance with OSHA requirements under 29 CFR 1910.120/1926.65 and USACE requirements (ER 385-1-92). The operating contractor will write the plan and submit it to the Corps' construction agent working on the contract. The construction agent will review and comment on the plan.

6.1.1 Routes of Exposure

"Routes of Exposure" refers to the ways a potentially hazardous material may interact with a worker or the surrounding environment. The primary routes of exposure considered in landfarming are:

- Inhalation of dust, aerosols or volatile constituents emitted from the landfarm;
- Ingestion of soil or waste in solid or liquid form;
- Absorption through the skin or mucous membranes through direct exposure to solids, liquids or vapors; and
- Migration of solids, liquids or vapors to the surrounding area via surface or groundwater, air, or attachment to clothes or equipment; leading to off-site exposure by one of the above routes.

Protective equipment and procedures specified in the HASP are intended to eliminate or minimize exposures and to protect workers and the surrounding area.

6.1.2 Personnel Protective Equipment

Many types of protective equipment are used on landfarming sites; as dictated by the type of wastes to which the area is exposed and the degree of contamination of the solid and liquid media. Typical basic safety equipment for personnel includes:

- ! Hard hat if required in the area (overhead pipes, other head contact);
- ! Hearing protection if loud machinery operation is operated (over 90 dB);
- ! Steel-toed boots to prevent foot injuries from drums or other heavy objects;
- ! Tyvek® or other dustproof clothing to minimize skin exposure;
- ! Safety glasses to protect eyes while equipment is running and to minimize dust exposure; and
- ! Gloves (typically some form of synthetic polymer such as butyl or Viton) which protect the worker from potential exposures.

Most of these items have safety standards established by ANSI, OSHA, or other standard-setting agencies.

If volatile hazardous compounds may be inhaled at levels above those permitted by NCGIH or other standards, respiratory protection must be available. Respirator cartridges available from several suppliers capture various types of potential contaminants, ranging from dust/mist to volatile organic compounds to beta particles. Manufacturers provide recommendations about the proper cartridge to use in a given exposure situation.

Most landfarms do not require respiratory protection during normal field operations except for dust/particulates. Respiratory protection is typically required only when a landfarm is operated in a temporary structure. A blower-induced negative air pressure is maintained in the building and an appropriate air filtration system treats the blower exhaust to protect the surrounding environment.

6.2 WASTE APPLICATION

The choice of waste application method for a landfarm depends on whether the intent of the operation is to "make clean soil dirty" or to "make dirty soil clean." At most hazardous wastes sites, the landfarm soil is essentially pre-loaded with waste and no waste application is required. For many refinery and petrochemical industry landfarms, the waste is applied to soil using equipment as described in Chapter 1.

6.2.1 Waste Loading Methods

All loading methods must avoid damage or compaction of the liner system. Wastes typically are loaded and soils spread using soft-tired or balloon-tired backhoes. Small track hoes may be used after soil or sludge placement in the treatment cell. Liners and protective layers (such as sand or gravel) must not be mixed with the soil to be treated, or moved away from their intended areas.

6.2.2 Depth of Lift

The practical depth of a lift in an in-situ hazardous waste landfarm is governed by the effective depth to which tillage aerates the soil. In extreme cases, e.g., homogeneous sand, lift depth can be 42 inches for a deep rake. For most landfarms, 18 to 24 inches is the deepest lift practical. For hazardous waste sites where a liner is required beneath the treatment cell, 6 to 18 inches is typical because rototillers or disc harrows must be limited to avoid damage to the liner. A good rule-of-thumb is for lifts to be 12 inches. The practical depth will also be dependent on soil type, waste content, and related factors.

6.3 AERATION

6.3.1 Rates and Frequencies

The landfarm is aerated (cultivated or tilled) on a schedule ranging from three times per week to once per month, as determined by the degradation rate and the ability of oxygen to penetrate soil pores. The landfarm size, depth of lift, soil and waste type influence the tillage method and equipment selected.

Tillage rates are based on the results of the treatability studies and system design but are almost always adjusted during operations based on practical experience and degradation results.

Table A-23 describes the conditions which affect decisions regarding tillage frequency.

It is important to understand that excessive tilling will not increase degradation rates but can damage soil structure and properties such that degradation rates are inhibited, because the binding properties of the clay in the soil are broken.

6.3.2 Methods

Most landfarms are effectively tilled using a tractor and disc harrow or rototiller similar to that used in crop farming or in road bed preparation. The equipment is readily available from farm implement dealers and supply stores (along with fertilizer). The equipment is generally rugged enough to cope with natural soil conditions, not difficult to maintain or decontaminate, and the equipment is reasonably priced.

Tilling may be performed first across and then along the soil contours within the treatment cell to minimize erosion and sedimentation against the landfarm berms. If a liner is present below the soil to be treated, the tilling implements must not penetrate the liner. Typically a gravel/sand armoring

TABLE A-23

Tilling Frequency

Effect/Condition	Effect on Frequency
Soil/sludge has poor tilth (poor loft, rapid recompaction)	Till more frequently to improve aeration
Soil is wet near the base of the treatment zone	Till more frequently to promote evaporation
Soil structure is weakening (tilth is decreasing)	Reduce tilling frequency, increase humic content
Heavy loadings, higher molecular weight (tarry) materials	Till more frequently

layer is installed above the liner to act as a buffer zone to prevent this type of penetration. The tilling of the armoring layer should be avoided. Most tilling implements have mechanisms for limiting the tilling depth.

For small or experimental landfarms, garden-size rototillers may be used as scaled-down versions of the tractor and tilling implements. The cost tradeoff between equipment and labor will dictate which is used.

For areas where the soil is well drained and no rocks are present, deep rakes may be used if no wastes are to be added to the system. These work particularly well where the soil must be treated to a depth beyond one lift, and space is limited. Deep raking is conducted at the same frequencies as tilling.

In some cases soil properties, moisture, climate and other factors may require multiple tillage methods. For example, a mold plow may be needed to lift recompacted or settled earth prior to rake or disc tillage.

6.4 SOIL AMENDMENTS

The soil (or other solids) in the landfarm require both monitoring for chemical change and amendments to keep the physical and chemical indicators in the proper ranges.

6.4.1 Moisture Control

The objective of moisture control is to maintain the optimum moisture level throughout the treatment zone. The target moisture content is affected by the soil (or sludge) type and the loading levels.

The most reliable parameter for monitoring soil moisture content is percent of field capacity, because the above factors are compensated for in the calculation. Field capacity itself is the maximum %-weight of moisture the unconfined, gravity-drained soil can retain. An example would be a sandy soil with a field capacity of 25%, meaning a maximum of 250 grams of water retained in 1,000 grams (dry wt.) of unconfined soil. Typically the target moisture content is expressed as a percent of the field capacity; for example, 50% of field capacity for the above sandy soil would be 125 grams water per 1,000 grams dry soil.

The target moisture content is in the range of 50-80% of the field capacity of the solid matrix, although a range of 20-80% will usually support microbial activity.

Soil suction measures the vacuum created above a closed water column by the suction (affinity of the soil for water) through a porous, fritted tip on the bottom of the tensiometer in intimate contact with the soil. Moisture meters determine moisture content by measuring galvanic currents generated by dissimilar metals in a probe in contact with wet soil.

Several products are commercially available to measure soil moistures. One typical device - the irrigation-type tensiometer - is a plastic tube, sealed at the top with an air-tight septum, with a fritted glass thimble at the bottom. The thimble is constructed so that water will not leave the thimble in an unconfined gravity drained state, but can be drawn from the thimble into the soil by the soil moisture tension or "suction". The vacuum induced by this soil suction is calibrated with a measured soil moisture content for the soil under test to determine the moisture content in the field. Various inexpensive models of this type of system are available through agricultural service companies.

Another conductivity measure is a gypsum block which wets and dries with the soil in which it is in intimate contact, and whose conductivity varies in relation to the water in the gypsum block. There are also direct conductivity measurements across the soil-filled gap between two electrodes. The conductivity of the soil varies with the water content (electrolyte solvent).

The "kick" test is a very crude test but has been used by Superfund sites to estimate soil moisture. Soil moisture content can be tested by kicking the soil - if it dusts, the soil is probably too dry; but if it sticks to your boot it is probably too wet.

Other devices are used to measure soil moisture based on conductivity, resistivity or other physical properties. These devices include gypsum blocks or open gap devices placed in the soil which measure changes in conductivity, resistivity or capacitance through the gypsum or across a standard set of gapped contacts in response to changes in moisture content of the gypsum block or the soil in the gap. These and other practical soil moisture monitoring devices such as lysimeters are available from companies such as:

- Heartland Tesh & Concord Inc.
  Fargo, ND
  (701) 280-1260

- Irrometer Company Inc.
  Riverside, CA
  (714) 689-1701

- Troxler Electronics Lab
  Research Triangle NC
  (919) 549-8661

- Soil Moisture Equipment Corp
  Santa Barbara CA
  (805) 964-3525

- CPN Corp
  Martinez CA
  (415) 228-9770

Other suppliers can be found through farm/irrigation equipment suppliers.

The suitability of any of these devices for a particular landfarm application needs to be considered carefully. In particular, the devices' interaction with waste components and the functional results of that interaction should be considered.

In areas where a net evaporation deficit causes water to be needed from an outside source, local well water is the preferred source, because there are no antimicrobial additives (e.g., chlorine). However, well water must be tested for Total Dissolved Solids (TDS) and the presence of metal and organic pollutants. Some local groundwater, such as that found in parts of the arid west, may be very high in TDS and specific metals such as arsenic. Repeated applications will cause a progressive accumulation of salts and metals in the soils, and hence increase the probability of requiring leachate treatment prior to discharge.

If a well cannot supply the necessary water, city water may be piped to the landfarm and treated for chlorine residuals if necessary. The water is added through soaker hoses or sprinklers (typically at the equivalent dose of approximately 1 inch of water per dosage day as a starting point) across the surface of the treatment area. The actual watering rate is dependent on factors such as precipitation, seasonal evaporation, and cultivation activities. The application rate should be altered as necessary to meet the design moisture content of the landfarm soils (as % field capacity or other measure). This design rate would be adjusted based on actual operating experience with that particular landfarm.

In areas where the water addition rate from precipitation may be high during parts of the operating season, increasing the tilling frequency can help to remove excess moisture through evaporation and more rapid gravity drainage to the sump. In many wet systems, more frequent tilling may be tolerated without damaging the soil structure; however, caution again is needed in tilling clays at high moisture content, as Overtilling will damage the soil structure.

6.4.2 Nutrients

Operationally, nutrient monitoring and adjustment occupy a large fraction of the operating time in a landfarm. While the nutrients are discussed separately below, the amendments are usually made simultaneously for as many nutrients as needed.

The primary nutrients (N & P) should be present above threshold levels to maximize the biodegradation of contaminants of concern. In practice, a moderate starting nutrient-N concentration (50-60 mg/kg as NH_4) may be selected and applied with additional amendments to sustain that or a lower concentration (10-50 mg/kg) in the soil. Application of very high ammonium or NO_2 concentrations can be toxic to microbes and promote a nitrification and denitrification cycle which wastes the nutrient by converting it to N_2.

To obtain maximum use of the nutrients, additions are typically made to attain an initial C:N:P ratio of 400:10:1, where C is carbon expressed as TPH or Oil & Grease. This avoids excessive, potentially toxic concentrations and somewhat suppresses the activity of nitrifiers/denitrifiers. The process is controlled and optimized to raise the degradation process to the maximum practical level.

One approach to minimize the number of nutrient additions required is the use of time-release fertilizers. Two major concerns must be addressed to successfully use these materials:

- the projected labor savings in applying them should be greater than their increased cost; and

- the release rate should be sufficiently linear to ensure that the matrix will not be overwhelmed initially and rapidly depleted by microbial consumption and leaching.

Nutrient contents of soils and managed water are often measured using field test kits. These kits are readily available, inexpensive, and sufficiently accurate to guide nutrient addition decisions and impacts. While no endorsement is implied, two reputable manufacturers of these types of test kits for soil and water testing are LaMotte Chemical Products Co. (Chestertown, MD; (800)344-3100) and Hach Company (Loveland, CO; (800)227-4224).

6.4.2.1 Nitrogen

Nitrogen (N) is the nutrient required in the greatest amount by the degradation process in a landfarm. Some N may be supplied by the contaminants (e.g., sludge or oil), but additions are usually necessary to meet the microbial demand.

The usual form of N amendment is as a commercial fertilizer. In commercial fertilizer specifications, N is the first of the three components listed (i.e., 33:3:3 refers to N:P:K). The N and P content is usually expressed as weight percent of N and P_2O_5 in the fertilizer. The potassium content, expressed as K_2O, in commercial fertilizers is much more significant for plants than it is for microbial nutrition.

For cases where a more concentrated form of N is desirable, urea may be used as a discrete N source which is rapidly converted to ammonia and CO_2 in the soil. The preferred form of N for the microbes is usually the ammonium ion, because this is easily assimilated.

Nitrates can have two roles in nutrient balance:

- nitrate can be assimilated by many microbes as a nutrient-N source, or

- nitrate can serve as an electron acceptor in place of oxygen (when oxygen is deficient).

Dissimilatory denitrification may become important in the deeper zones of the landfarm, as water carries more mobile nitrates produced by microbial ammonia oxidation (nitrification) into oxygen-limited depths. The nitrate content of the sump water may affect the disposal options available, because surface discharges control the discharge of nitrates under drinking water regulations.

Both ammonia-N and nitrates/nitrites are readily measured using field test kits. The kits test water samples prepared from sludge or soil samples slurried in water to provide an aqueous matrix for the test. The sump water may also be used as an indirect indicator of the soil nutrients, particularly with routine monitoring following nutrient additions.

6.4.2.2 Phosphorus

Phosphorus is the second primary nutrient which typically requires monitoring and addition to properly manage the remediation. It is usually required at approximately 10% of the N concentration. As described above, phosphorus is also a part of commercial fertilizers and is usually added as such.

As with N, the chemical form of the P affects its utilization by the soil microbes. The most "available" form (easiest for the microbes to assimilate) is ortho-phosphate. However, calcium (a common element in most soils) will precipitate the ortho-phosphate and render it less available for microbial nutrition. There are several complex phosphate forms which can supply the nutrient, such as tripolyphosphates and metaphosphates, which may provide the necessary material in more soluble (and hence somewhat more available) form.

The field test kits used for phosphate measurement detect the ortho form, and the results thus may be biased low. However, the presence of non-ortho phosphorus at low to moderate concentrations is not deleterious and in practice is usually ignored in operations. The test is usually run on aqueous samples; an extraction/filtration may be performed on soil or sludge as described above for N. Laboratory testing may be performed for either ortho or total phosphate to confirm field test results.

6.4.2.3 Trace Nutrients

Trace nutrients are metals which are trace constituents of cells used in various metabolic processes, and usually present in soils. "Micronutrient" deficiency, while rare, is usually detected during the treatability study if nutrient-enhanced samples do not exhibit dramatic performance improvements over controls. Although micronutrient control may prove practical in the future to enhance treatment kinetics, the prediction and control of trace nutrients is impractical at present.

6.4.3 pH Control

Microbial processes which degrade hydrocarbons also affect the pH of the treatment system. by the generation of $C0_2$ and other acidic end products, which dissolve in the soil water. An unbuffered soil system with a neutral pH (7.0) can rapidly become sufficiently acidic to slow microbial activity. Soil (pH 4.5-5.0) liming or some equivalent will help neutralize the soil/water pH, as illustrated by this chemical equation:

$$CO_2(gas) \rightleftharpoons CO_2(dissolved) + H_2O \rightleftharpoons H_2CO_3 - H^+ \rightleftharpoons HCO_3^- - H^2 \rightleftharpoons CO_3^-$$

A field test kit for buffering capacity of the soil should be used to determine how much lime should be added to keep the proper cation (buffering) balance. This approach can be used to anticipate pH changes and allow correction **prior** to significant pH change.

Lime or other amendments should be added in conservative, calculated doses, because too much lime can shock and "burn" the system. For this reason, limestone rock is often used because it slowly dissolves in water-filled pores and thus gradually buffers soil pH. Table A-24 lists pH control materials and recommendations regarding their application. Well-buffered soils will require less amendment, but testing should be conducted regularly to ensure that soil pH remains acceptable.

TABLE A-24

pH Control Materials

Chemical/Material	Advantages	Disadvantages
Base Amendments		
Lime (Quicklime)	Inexpensive, available	Potent- may burn if overapplied
Limestone	Requires more additive, adds bulk	Works gradually, time-release effects
Caustic solutions (NaOH)	May be added in liquid form, dilution can be controlled	Dilution must be carefully controlled, may shock system
Sodium Bicarbonate	Less caustic shock, easier to handle, good buffer	More expensive
Acid Amendments		
Acidic Additives (HNO_3, H_3P0_4)	Nutrient based acid, added as liquid.	Handling precautions, cost

6.4.4 Oxygen Addition

A relatively recent development in landfarming is the application of calcium peroxide as a supplemental electron acceptor. The material is tilled into the soil with other nutrients to enhance the oxygen concentration in water-filled pore spaces by decomposing into oxygen and dilute caustic (which may help with pH control) Data on the effectiveness of this process is scarce; it may be related more to chemical oxidation of compounds by hydrogen peroxide (H_20_2). If considered, two potentially deleterious effects should be investigated during the treatability phase:

- decomposition limiting effect resulting from increased pH (in poorly buffered soils) and consequential inhibition of microbial metabolism, and
- sterilizing effects resulting from production of H_20_2 and its destructive effects on microbes.

6.5 BIOAUGMENTATION

Virtually all landfarms operate successfully utilizing microbes indigenous to the soils or solids being treated. Hydrocarbon degraders are ubiquitous in soil, thus landfarms do not typically require bioaugmentation, inoculation, or the addition of microbes "designed" to degrade the known constituents of wastes. Little evidence exists in the available scientific literature to support claims that augmentation treats contaminants better than the indigenous microorganisms. Some studies show that it does not enhance treatment of more xenobiotic contaminants (Lewardowski et al., 1986; Goldstein et al., 1985; Zaidi et al., 1988). The American Academy of Microbiology (AAM, 1992) indicated that augmentation is, however, an open research problem with little fact or research to support either augmentation or non-augmentation.

6.6 PROCESS START-UP REQUIREMENTS

Equipment requirements for start-up include:

- functional water pumps from sump to treatment, to sprinklers and/or disposal,
- leak-tight piping and equipment,
- operation and calibration of air monitoring systems (if needed),
- inspection of berms and sump,
- tillage equipment operational and properly maintained,
- nutrient storage containment integrity, and
- leachate storage containment integrity.

6.7 SITE MAINTENANCE

6.7.1 Dike Maintenance

Dikes or berms surrounding the treatment area are usually critical to the success and regulatory compliance status of the remediation process and require periodic maintenance. Since most berms are constructed of compacted soil (often native), the degree of compaction of the berm soil and any protection such as synthetic liners or clay layers will affect the useful life span of the berm. Testing and (if necessary) recompaction to meet design standards is recommended at least annually to prevent loss of berm integrity, which may be caused by water pressure in the treatment area, particularly in the sump area. Heavy rains may create sufficient head to collapse the wall and leak a large volume of water into the surroundings, which usually must be reported as a spill.

Dikes or berms should be inspected every time the landfarm is tilled or after an event occurs (such as local flooding) which might affect berm integrity.

6.7.2 Liner Maintenance

Liner inspection is usually performed on a spot basis by digging through the soil matrix to the liner in randomly selected locations. Excavated material is replaced after inspection, presuming that no leaks are detected.

The most common source of liner failures during operations is tillage. Materials shift during treatment, creating shallow spots which when tilled to uniform depth do not protect the liner below the shallow area. Liner inspections should focus on identifying these shallow areas. Another source of liner tears is stones or rocks which are ground into the liner by the tillage machinery. Low surface pressure tillage equipment is recommended to reduce the potential for tears and to minimize recompaction.

Liner repairs may be made by continuing the inspection excavation to expose the entire tear and patching it, followed by replacement of the excavated material over the patch.

6.7.3 Piping and Equipment Maintenance

Piping maintenance is only required to repair leaks, and usually consists of replacing hoses or pipe sections. Since water is being pumped across the treatment area, a small leak within the treatment area which does not affect water flow rate can be tolerated.

Maintenance of the pump flow rates and delivery of rated head are critical to the performance of sprinkler systems or soaker hoses in water and fertilizer distribution and application rates. Maintenance may consist of changing impellers, unblocking lines or strainers, or replacing connections.

Water treatment equipment maintenance should be performed in accordance with the manufacturer's instructions and the design Operation & Maintenance tables.

7.0 SAMPLING AND VERIFICATION PROCEDURES

7.1 WASTE DEGRADATION MONITORING

The disappearance of waste constituents (a compound specific approach) or appearance of end products (CO_2, biomass, intermediates) (i.e., the collective approach), can be used to monitor waste degradation. Monitoring both is best, but is expensive and may not be practical.

The approach(es) used must adequately demonstrate that the wastes have actually been remediated rather than simply transformed or translocated.

Progress monitoring usually focuses on specific organic compounds, whereas control monitoring focuses on other parameters. In a successful bioremediation landfarm, organic (carbonaceous) compounds are degraded to CO_2, water, relatively stable organic soil constituents, and microbial biomass. In actual landfarm operations, measuring water and CO_2 as end products is usually impractical. Usually water measurements are not sensitive enough to detect a change in water content of the soils due to degradation products. The various other sources of water gain and loss can not be controlled and accounted for. Similarly, carbon dioxide levels in the soil can be measured but their origin is not certain and the concentrations are dependent on many factors such as soil moisture, temperature, pH, ambient air conditions, etc.

7.1.1 Parent Compound

Usually, concentrations of both collective parameters and indicator compounds (specific chemical constituents which are representative of a larger group of constituents, and whose degradation is considered representative for the group) are established at the beginning of the landfarming process. Often, the indicator selection is based on the compound's toxicity, persistence or concentration.

A grid pattern for sample locations is laid out across the landfarm and samples are collected at grid nodes to establish an analytical baseline. These locations will be periodically resampled during the landfarming process.

7.1.1.1 Concentration Reduction

Remediation progress is measured by the disappearance of constituents of concern (individually or collectively) relative to their initial concentrations. Monitored forms can be specific compounds (e.g., volatile or semivolatile organic compounds) or collective parameters (e.g., TPH or O&G). A decrease in specific or collective parameters indicates that remediation is occurring. Because the carbon dioxide concentration in landfarm soils cannot be easily measured, the material balance emphasis is usually based on disappearance of waste constituents. Little can be done in the field to identify intermediate decomposition products or their concentration unless they accumulate in the landfarm soils, and can be analytically identified as discussed in Section 8.1.2.1.

7.1.1.2 Toxicity Reductions

Remediation progress can also be measured by changes in the toxicity of the soils (e.g., by Microtox® tests) as compared also to the initial baseline test results (Section 4.0).

7.1.1.3 Volume Reductions

If the waste content of the landfarm is very high, a volume reduction will occur during landfarming due to conversion of hydrocarbons to $C0_2$ and water. Volume reduction is a poor progress indicator because it is difficult to assess.

7.1.2 Transformation/End Products

Waste constituents will be changed by degradation to essentially stable end products such as carbon dioxide, water, and salts, or will be transformed into intermediates which may be more or less hazardous than the parent compounds. Transformation products may not be readily identified by the standard analytical procedures. Collective analytical parameters such as TPH, HO&G, TOX, or TOC may be useful for this purpose, because they usually detect responses by the unknown intermediates also.

Any assessment of incorporation of waste constituents into biomass (microbial cells) must be estimated or assumed. The amount can range up to approximately 45 - 50% of the available organic carbon but is dependent on multiple variables in the process. Certain conditions, such as low oxygen or negative oxidation/reduction potential will usually favor the transformation to intermediate end products, which can also cause odors.

7.1.2.1 Organic

Monitoring the remediation products of hydrocarbons requires detailed analytical methods usually involving VOC or SVOC analyses [e.g., SW-846 methods 8015, 8020, 8240, and 8270] (USEPA, 1986d), to measure changes in concentrations of specific suites of compounds as the organic carbon content drops. Since specific analyses are generally more expensive than collective parameter methods, they are typically analyzed less often to track the progress of remediation.

Tracking products of the bioremediation provides a basis for material balance calculations to estimate the fate of waste constituents, which is essential in demonstrating that bioremediation/mineralization is occurring.

Carbon dioxide is the key to material balance but is typically very inaccurately measured except under very carefully controlled conditions. Such measurements may be useful in treatability studies but often prove impractical at full-scale.

7.1.2.2 Inorganic

For inorganic compounds, samples collected at the beginning and end of each lift treatment normally suffice for mass balance. Heavy metals can usually be kept immobilized with an adequate soil pH control program.

A variety of factors, such as oxidation or reduction state, soil water content, pH, microbial transformations, etc., can alter the metals' analytical extractabilities and thus artificially skew the apparent concentrations in the soil/waste.

7.2 MICROBIAL MONITORING

Typically, landfarming programs monitor numbers of microbes, usually by plate counts or MPN estimates of total heterotrophic bacteria, augmented perhaps with counts of specific hydrocarbon degrader bacteria. As discussed in Section 4.2.3.1 these results never measure all the biomass. These counts are primarily useful in addressing the trend growth/death trend of a microbial population since they can measure only viable cells not all soil microbe biomass (living and dead)

7.3 SOIL MOISTURE MONITORING

As discussed in other sections, soil moisture is a key parameter for controlling landfarming. Soil moisture can be an ambiguous term, but in landfarming usually means percent field capacity. See Section 6.4.1 for an explanation of field capacity and moisture measurement techniques.

When the field capacity of the soil/waste is known, the appropriate range of operational moisture contents can be estimated for both the treatability and, if necessary, the full-scale process design, although moisture requirements should be tested in the treatability studies. As a general rule, landfarming operations try to maintain a moisture content of 40 to 60% of field capacity.

Soil moisture will vary with depth from surface dryness to near saturation at the base. The moisture content is usually monitored at mid-depth of the tillage zone using a tensiometer or in a full vertical sample from the tillage zone after thorough mixing. This known moisture relative to the optimum is used to estimate the pounds or gallons of water to be applied on average over the treatment unit.

7.4 NUTRIENT LEVEL MONITORING

Nutrients (N and P) are monitored in the soil and sump water using field test kits, with the results used to guide weekly or monthly nutrient amendments. These "kits" can be purchased from various vendors and are commonly used for agricultural, soil conservation, and similar purposes to rapidly determine various soil and water analytical parameters. These kits are useful, real-time, and generally accurate to the degree necessary for field guidance purposes. Most use well established chemistry/spectrophotometric or color-comparative techniques. Laboratory confirmation tests are periodically required to confirm test kit results. Both ammonia-N and nitrogen oxide-N (nitrate/nitrite) are measured to determine total available nutrient-N. Soil sampling is done at nodes across the entire landfarm and at depth in the tillage zone to determine localized deficiencies.

7.5 pH MONITORING

Soil pH is usually measured in the field or on site using standard soil pH methods and a standard calibrated pH meter, colorimeter, or litmus paper. Typical target ranges are 6 to 8 standard units, although some systems can operate effectively between 5 and 9. Oxidation/reduction potential (ORP) supplements the pH measurement; at a very low (-) ORP, anaerobic biological process are favored and the potential for odor generation and non-oxidative transformations of wastes is higher.

Soil pH is typically measured monthly or less frequently in well buffered soils. The frequency of measurement can be changed based on the extent of change seen during operations. Samples should be representative from across the landfarm and through the full vertical depth of the tillage zone.

7.6 SAMPLING/ANALYSIS PROCEDURES FOR CONSTITUENT CONCENTRATION DETERMINATION

7.6.1 Sample Collection

Landfarm soil samples are collected as grabs of the full vertical depth of the tillage zone at grid nodes across the landfarm. Several grab samples from an area may be composited depending on soil volume of the sampling grid area (e.g., $\leq$ 100 cubic yards) and applicable regulations and approved operations plans. Sampling can be done with split spoons, hand augers or corers, or trowels or shovels. Table A-25 contains guidance for sampling, compositing, preservation, shipping, labeling and chain-of-custody procedures.

Water samples may be collected directly from the sump, taken from lysimeters placed in the treatment zone, or from monitoring wells placed in and around the treatment unit. The lysimeter samples are more difficult to collect but provide direct analysis of soil water conditions.

The samples need to be placed in suitable containers, properly preserved, properly labeled as to sample origin and analyses desired, and accompanied by a chain-of-custody document. This ensures defensible data for project documentation.

7.6.2 Decontamination

The instruments used to collect any sample must be free from extraneous contamination. U.S.EPA , some states, and standard organizations have guidance for the decontamination of sampling equipment, from drill rigs to hand augers. Initial cleaning usually consists of scraping to remove gross soil, water washing, alkaline detergent cleaning, water rinse, and often a methanol (or other fast-drying solvent) rinse. The apparatus is then air dried prior to subsequent use in sampling. Larger items, such as drill rigs, are typically cleaned using steam or high pressure water between sample locations.

Materials used for decontamination should be disposed of properly. Solvents in particular must be handled and disposed of safely. These materials are usually segregated by matrix and stored in drums for later appropriate disposal.

TABLE A-25

Typical Analytical Methods Utilized for Landfarming Operations

Method[1,2]	Description	Type[3]	Typical Cost
MCAWW 413.1	Total Recoverable Oil and Grease[4]	C	$50
MCAWW 418.1	Total Recoverable Petroleum Hydrocarbons[4]	C	$50
SW 846: 6010	Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP)	S	$15/element
SW 846: 7000	Atomic Absorption Methods (AA)	S	$30/element
SW 846: 7471	Mercury in Solid or Semisolid Waste (Manual Cold-Vapor Technique)	S	$30
SW 846: 8010	Halogenated Volatile Organics	S	$150
SW 846: 8015M	Nonhalogenated Volatile Organics[5]	C	$100
SW 846: 8020	Aromatic Volatile Organics	S	$75
SW 846: 8240	Gas Chromatography/Mass Spectrometry for Volatile Organics	S	$225
SW 846: 8270	Gas Chromatography/Mass Spectrometry for Semivolatile Organics: Capillary Column Technique	S	$400
SW 846: 9045	Soil pH	C	$10
SW 846: 9060	Total Organic Carbon	C	$50
SW 846: 9070	Total Recoverable Oil and Grease[4]	C	$50
SW 846: 9071	Oil and Grease Extraction Method for Sludge Samples[4]	C	$50

[1] - SW 846: Test Methods for Evaluating Solid Waste Physical/Chemical Methods, 3rd Edition.
[2] - MCAWW: Methods for the Chemical Analysis of Waters and Wastes, EPA-600/4-79-020, March 1983.
[3] - C is for collective methods; S is for specific methods.
[4] - These methods utilize fluorocarbon-113 which will be banned in January, 1995. Laboratories will replace these methods with Standard Methods for the Examination of Water and Wastewater (18th Edition) method 5520B (Partition-Gravimetric Method) or SW 846: 1664 (Total Petroleum Hydrocarbons).
[5] - This method is frequently cited for Total Petroleum Hydrocarbon (TPH) methods by gas chromatography. This method does not describe the analysis of TPH; however the principles in this method are applied to the analysis of samples for gasoline, diesel and other fuel oils using gas chromatography with flame ionization detection.

7.6.3 Analytical Methods

Analytical methods are described in detail in the guidance documents listed in Table A-25. Generally soil/sediment and groundwater samples are extracted and analyzed by SW-846 (USEPA, 1986d) or CLP methodology (USEPA, 1991), while surface water samples are extracted and analyzed using EPA 600 methods (USEPA, 1983c) and EM 200-1-3. Specific guidance for choice of appropriate methods is given in Appendix D (Guide to the Preparation of the Chemical Data Acquisition Plan) of ER 1110-1-263 (Chemical Data Quality Management for Hazardous Waste Remedial Activities).

The construction/operator contractor also should use CEGS 01450 - Contractor Chemical Data Quality Control (December, 1994) and EM 200-1-3 Requirements for the Preparation of Sampling and Analysis Plans (September 1994).

Table A-25 summarizes typical analytical methods utilized during landfarming operations.

7.6.4 Frequency

Soil samples are typically collected monthly or bimonthly, depending on the level of contamination, tillage frequency and nutrient additions, and expected progress of remediation. Water samples are collected and shipped with soil samples. Many analytical programs have collective parameters measured on composite samples monthly, and specific analyses done quarterly for cost control.

7.6.5 Quality Assurance/Quality Control

Quality control/quality assurance (QA/QC) is dictated by the data quality objectives or the use of the data. Details of the QA/QC requirements for a project will be described in the Chemical Data Acquisition Plan (CDAP) and in EM 200-1-3, Requirements for the Preparation of Sampling and Analysis Plans. An outline and requirements for the CDAP are given in ER 1110-1-263 (October 1990).

7.7 STATISTICAL ANALYSIS PROCEDURES

At the onset of a project, a database should be initiated which will include (at a minimum):

- sample locations,
- field identifications,
- date sampled,
- date analyzed,
- analytical parameters,
- analytical results,
- quantitation limits, and
- qualifiers.

Popular database programs such as dBase IV®, Paradox®, or Access® can be utilized for this purpose. Laboratories can provide diskette data in spreadsheet format (Lotus 123®, Quatro-Pro® or Excel®) or ASCII-delimited text for transfer into a database program. The information in the database is then sorted and queried to provide information for statistical evaluations, trend analyses or reports to agencies or clients. This data can also be imported into spreadsheet files for statistical analysis. Statistical evaluations of data include averages, standard deviations (sample) and T-tests. T-tests will indicate whether there is a statistically significant decrease in collective or specific concentrations from initial tests to intermediate or final monitoring. Outlier tests can be utilized to find spurious analytical results which may include transcription errors. Generally analytical data from multiple samples during one sample event are averaged to obtain a representative concentration for the site.

7.8 <u>INDEPENDENT PARTY VERIFICATION / CERTIFICATION</u>

The US Army Corps of Engineers (USACE), Hazardous, Toxic and Radioactive Waste (HTRW) Center of Expertise (CX) at the Missouri River Division certifies laboratories for use on COE projects by procedures dictated by COE EM 200-1-1, Validation of Analytical Chemistry Laboratories.

8.0 MATERIALS OF CONSTRUCTION

8.1 LINER MATERIALS

8.1.1 Recompacted Clay Liners

Recompacted clay is the most common lining material, because it has a low material cost and wide-spread availability. Recompacted clay layers are typically required to have hydraulic conductivity values below 10^{-6} to 10^{-7} cm/s, depending on regional requirements. Typical clay liner thicknesses range from 0.5 to 1.0 meter (1.5 to 3 feet). However, the thickness for any specific site must be determined as discussed in Section 3.0 - "Regulatory Requirements."

Since the material properties of clay vary regionally, site-specific material requirements must be developed, usually in consideration of local borrow sources. The adequacy of a borrow source may be determined through laboratory testing or construction of a test pad (see previously mentioned EPA documents) in which the borrow source and construction methods are tested. This procedure is expensive. In lieu of this operation, the operators of the borrow source or local geotechnical engineers may have a database on the available borrow sources, with installation procedures that meet the desired permeability. See Corps of Engineer Military Guide Specification 02443 - Low Permeability Clay Layer when specifying requirements for a clay liner.

The primary advantages of recompacted clay liners are:

- low material costs (particularly when borrow sources are available on site),
- they are extremely durable and less susceptible to damage due to over-tilling, and
- they are easily repaired with readily available equipment.

The primary disadvantages of recompacted clay liners are:

- Installation costs are moderate to high.

- The clay mineralogy requires water to fully hydrate and form the "tightest" barrier. Non-aqueous phase liquids (NAPLs) may interfere with the clays' bi-polar structure and degrade the clay liner, thereby increasing permeability.

- Clay liners are subject to freeze/thaw damage and desiccation cracking.

8.1.2 Geosynthetic Clay Liners

Geosynthetic clay liners (GCLs) typically consist of a thin layer of bentonite either sandwiched between two geotextile layers or bonded to an HDPE sheet. When hydrated, the bentonite layer swells to form a hydraulic barrier layer and typically has a liquid permeability of approximately 1010 cm/s. This type of liner system has been used as a substitute for all or portions of standard recompacted clay liners in many regions, particularly where suitable clay sources are scarce.

Its major advantages are:

- Self-healing properties for small punctures, and
- Low cost and speed of installation.

Its major disadvantages are:

- Material costs are moderate to high.

- The bentonite layer requires water to hydrate the hydraulic barrier. In the presence of non-aqueous phase liquids (NAPLs), the bentonite may not fully hydrate to form the intended hydraulic barrier.

- Extreme care must be taken to avoid damaging these liners during construction or operation of the landfarming unit. Often sacrificial soil or gravel layers are placed over the liner to prevent damage resulting from heavy equipment usage.

- Because of the very thin nature of the barrier layer, GCLs form poor barriers against vadose zone migration of contaminants.

Because agency acceptance of this type of liner has varied significantly, pre-approval is prudent before specifying this material. The main specification item is the amount of bentonite by weight per square foot because it controls the permeability of the liner. See Corps of Engineers Military Guide Specification 02442 - Geosynthetic Clay Liners when specifying requirements for this type of material.

8.1.3 Geomembrane Liners

Geomembrane liners are plastic films placed over the bottoms, sides and caps of landfarms and landfills to control leachate migration. Liner materials may consist of:

- high density polyethylene (HDPE),
- chlorinated polyethylene (CPE),
- chlorosulphonated polyethylene (Hypalon), and
- polyvinyl chloride (PVC).

The thicknesses of these materials range from 20 to 120 mils, depending upon the application. Standard design considerations and construction specifications can be found in CEGS 02271, "Waste Containment Geomembrane" and *NSF International Standard,* "Flexible Membrane Liners," NSF 54-1993 (NSF, 1993).

Of these, HDPE has become the most commonly used material because it is resistant to chemical, ultraviolet and biological degradation. These materials have extremely low measured permeabilities ($<10^{-13}$ cm/s), making them virtually impermeable to leachate or gas generated in landfills and landfarming units. These HDPE liners are typically 40 mils thick for non-hazardous applications and 60 mils thick for hazardous applications.

Geomembrane liners typically consist of large panels whose ends are anchored in trenches. The panels are then rolled out and placed on top of prepared subgrade or clay liners, and the panels are welded together with a double seam, referred to as a "wedge" weld. This wedge weld allows each seam to be either vacuum or pressure tested to ensure the integrity of the liner.

Major advantages of geomembrane liners are:

- low permeability to leachates and gases,

- low to moderate installation costs, and

- ability to perform "leak" testing during construction.

Major disadvantages are:

- These materials can be degraded when exposed to strong chemical solutions and condensates. These materials are particularly susceptible to strong organic solvent solutions.
- Extreme care must be taken to avoid damaging these liners during construction or operation of the landfarming unit. Often, sacrificial soil or gravel layers are placed over the liner to prevent damage resulting from heavy equipment usage.

- Material costs are moderate to high.

8.1.4 Asphalt and Cement

Asphaltic and Portland cement concrete are not normally specified as original liner materials for landfarming, but they have been used often in actual landfarms for industrial sites. Often, an unused parking lot can serve as a site for landfarming. These "pads" are durable, can withstand the loads of tractors and tilling equipment and are often built with the proper slope for drainage. Gravel or sand/gravel mixes can be placed directly on the pavement to promote leachate collection and prevent damage during operations. They are usually large enough to treat large quantities of soil in one lift.

This can save the cost of constructing a complete lining system provided the risks resulting from low quantities of contaminant migration are acceptable. Soils contaminated with non-hazardous levels of methanol, fuel products, etc., are often landfarmed directly upon the nearest available parking lot. Typically the use of this type of lining system must be negotiated with the regulatory agency on a site-by-site basis.

Asphalt parking areas will require a close inspection and patching in order to minimize infiltration of leachates. The asphaltic concrete course should be a minimum of 6.3 cm (2.5 in.) thick. The pavement should preferably be seal-coated prior to the application of protective gravel layers or waste soils. In contrast to asphaltic concrete pavements, macadam pavements typically provide poor resistance to leachate migration. Where they are to be used, these pavements are typically covered with an additional lining material (asphaltic concrete, geomembrane, etc.).

If a Portland cement concrete parking area is used, patching may be required. Timber or fibrous expansion joints should be sealed with commonly available elastomeric sealants in order to minimize the permeability. Highly fractured Portland cement concrete pavements have also been covered with a seal-coat or an asphaltic wearing course to minimize leakage.

In some cases, concrete curbs or side walls may also be constructed where space restrictions do not allow earthen berms to be constructed. Where these side walls are to be joined to existing concrete pavement, epoxy joint compounds should be used in accordance with ACI 350R - "Environmental Concrete."

The side walls (berms) are often constructed using locally available clean soil. These soils should be compacted to appropriate structural fill requirements. The critical construction design element for these systems is the sealing of the interface between the side wall and the bottom. Medium to highly plastic clay soils have been successfully used to construct the berms. Where primarily sandy or gravely soils are available for berm construction, a thin (typically 5 cm) layer of clay is placed along the soil/asphalt interface and "buttered" to create a leakproof seam.

8.2 PUMPS

Pumps, as well as other stormwater conveyance equipment, should be selected to match the intended service conditions. Stormwater and leachate may have the following properties:

- High total suspended solids (TSS) content (50 to 250 mg/l) because of the "tilled" nature of the soil;
- Low pH (4 to 7) resulting from biological activity if buffering capacity is not maintained; and
- Concentrations of waste constituents.

Guidance for pump construction materials can be found in the following guide specifications:

- CEGS No. 11211 - "Pumps: Water, Centrifugal,"
- CEGS No. 11212 - "Pumps: Water, Vertical Turbine,"
- CEGS No. 11310 - "Pumps: Sewage and Sludge."

8.3 PIPING AND HEADER MATERIALS

The two types of materials which have principally been used for landfarming systems are steel and plastic. Because of its inferior corrosion resistance compared to plastic pipe, steel pipe is not recommended for use in land farming. Plastic piping materials can be divided into two basic groups; thermoplastic plastics and thermosetting plastics. More specific discussions of each of these materials are provided in subsequent sections.

When selecting the material to use, a number of factors should be considered. Ultimately, the service life of a pipe material will depend on the material's durability and the conditions to which it is exposed during service. The durability of a plastic depends on the polymer, the auxiliary compounding ingredients, the manufacturer, and the installation of the product. The durability of plastics can vary greatly with respect to different exposures.

Strength considerations for both PE and PVC pipes have been extensively researched and are well documented in manufacturers' literature. Published strength characteristics are specified at certain temperatures.

For a more complete discussion of the above factors, the reader is referred to the manufacturers' literature and the following guide specifications:

- CEGS No. 02720 - "Storm Drainage System," and
- CEGS No. 02730 - "Sanitary Sewers."
- CEGS No. 02732 - "Force Mains and Inverted Siphons."

The criteria in these specifications are applicable to most non-hazardous landfarming applications. Additional guidance for the specification of commonly used corrugated polyethylene drainage piping systems can be found in the American Association of State Highway and Transportation Official Standard Specification M252, (AASHTO, 1990).

However, where leachate or stormwater is RCRA hazardous or may contain constituents at concentrations which are harmful to human health or the environment, more stringent piping criteria, such as chemical resistant or double-walled piping, may be required.

8.4 STORAGE TANKS AND IMPOUNDMENTS

Leachate and contact stormwater may be retained in either earthen impoundments or field-erected tanks. If earthen impoundments are used, the establishment of design criteria for liners should be performed in a similar manner to the methods outlined in Section 5.6 - "Liners and Leachate Collection Systems." A detailed discussion of the advantages and disadvantages of liner types is included in Section 8.1.

Although geomembrane liners have been used on a number of sites, care must be taken when designing below-grade impoundments with these liners to prevent the liner from "floating." This "floating" may result from intrusion of shallow groundwater or from the development of naturally occurring biogenic gases.

Floating of the liner will reduce the storage capacity of the impoundment and may rupture the liner.

Typically, carbon steel, field-erected tanks have been used to provide storage for:

- Leachate,
- Contact stormwater, and
- Nutrients.

Contact stormwater and leachate from properly operated treatment units (where pH is adequately controlled) is not significantly corrosive. Therefore, properly primed and painted steel tanks provide adequate service. All field-erected tanks should comply with the requirements of the American Petroleum Institutes Standard Specification No. 650, *Welded Steel Tanks for Oil Storage* (API, 1988).

9.0 DESIGN AND CONSTRUCTION PACKAGE

This section describes the USACE regulations applicable to the design and design documents that must be included in the design and construction package. The design and construction package includes:

- Design Analysis,
- Contract Drawings, and
- Contract Specifications.

These requirements are discussed below.

9.1 APPLICABLE USACE DESIGN POLICIES AND REQUIREMENTS

The following USACE regulations apply to the development of design documents in their various stages for the USACE:

Regulation	Title
ER 1110-345-710	Engineering and Design - Drawings
ER 1110-345-100	Engineering and Design - Design Policy for Military Construction
ER 1110-345-700	Engineering and Design - Design Analyses
ER 1110-345-720	Engineering and Design - Construction Specifications
ER 1165-2-132	Water Resources Policy and Authorities- HTRW Guidance for Civil Works.
ER 1180-1-6	Construction Quality Management

Other regulations should be applied as applicable.

9.2 DESIGN ANALYSIS

This section outlines the various design packages that are typically required by either regulators, system installers, or system operators. USACE-CEGS guidance specifications, which are typically included in each design document, are listed beneath each design component.

9.2.1 Work Plans

A project Work Plan should consist of:

- Work Management Plan,
- Field Sampling Plan,
- Quality Assurance Project Plan, and
- Site-Specific Safety and Health Plan.

9.2.1.1 Work Management Plan (WMP)

The WMP defines the scope of services, level-of-effort, costs, schedule, organization, responsibilities, and other summary project information. Recommended minimal elements of a WMP include:

- Title Page
- Table of Contents
- Statement of Work
- Project Description
- Site Background
- Site Geology
- Site Hydrogeology
- Project Organization
- Project Responsibilities
- Objectives
- ARARs
- Schedule of Activities
- Costs

9.2.1.2 Field Sampling Plan (FSP)

The FSP provides guidance on the methods to be used for field sampling and data gathering activities. Recommended minimal elements of a FSP include:

- Sampling Objectives
- Sampling Location/Frequency
- Sampling Identification
- Sampling Equipment
- Sampling Procedures/Protocol
- Sample Handling/Packaging/Preservation/Shipping
- Sample Custody/Chain-of-Custody Forms
- Analytical Parameters

- Decontamination Procedures/Methods
- Management of Derived Waste
- Preventative Maintenance
  - Procedures/Schedules/Documentation
- Documentation

9.2.1.3 Quality Assurance Project Plan (QAPP)

The QAPP provides guidance on meeting the Data Quality Objectives. Recommended minimal elements of a QAPP include:

- Data Quality Objectives
- QA Objectives for Measurements
  - Precision
  - Accuracy
  - Completeness
  - Representativeness
  - Comparability
- Analytical Procedures
- Data Reduction, Validation, and Reporting
- Internal Quality Control
- Performance and System Audits/Frequency
- Preventative Maintenance Procedures/Schedules
- Specific Routine Procedures Used to Assess Data
- Corrective Actions
- Other Project Specific Requirements
- Quality Assurance Reports to Management

9.2.1.4 Site Specific Safety and Health Plan (SSHP)

Provides a description of the potential physical or chemical hazards present at the site, to provide emergency information in case of injury or illness, and to describe the dermal and respiratory protective clothing or equipment required of all personnel for each phase of the field work. Outline to be detailed to specific project requirements.

9.2.2 Design Analysis Requirements

- Biological/Chemical
- Treatability Study
- Geology/Hydrogeology
- Hydrology
- Geotechnical

- Environmental
- Architectural
- Structural
- Mechanical
- Electrical
- Health and Safety

9.2.2.1 Records

- Data for Waste
- Aerial Map of Treatment Facility
- Topographic Elevation Map
- Equipment Literature/Catalog
- Environmental Performance Criteria
- Correspondence

9.2.3 Plan and Drawings

- Process Cell and Unit Location drawings
- Equipment layout
- Equipment List
- Mechanical drawings
- Civil drawings
- Electrical Drawings
- Typical Construction Sections and Details

9.2.4 Potential List of Specification Sections

Provided below is a list of potential specifications that should be included in the contract documents. Not all specifications will be applicable to every project. Corps of Engineers Guide Specifications for Military Construction are shown when available. If no guide specification exists, experience from previous sites or manufacturer specifications should be modified by the design engineer to create a construction specification.

DIVISION 1 - GENERAL REQUIREMENTS

01110 safety, Health, and Emergency Response
01300 Submittals Procedures
01440 Contractor Quality Control
01450 Chemical Data Quality Control
01XXX Summary of Work

01XXX Order of Work
01XXX Contractors Use of Site
01XXX Pre Construction and Pre Work Conference
01XXX Progress Meetings
01XXX Special Clauses
01XXX Measurement and Payment
01XXX Special Project Features
01XXX Warranty of Construction
01XXX Construction General
01XXX On-Site Camera
01XXX Dust Control
01XXX Spill and Discharge Control Plan
01XXX Off-Site Air Monitoring
01XXX Bulky Debris Removal and Disposal
01XXX Environmental Protection
01XXX Security
01XXX Regulatory Requirements
01XXX Decontamination and Disposal
01XXX Surveys for Record Drawings
01XXX Photographic Documentation
01XXX As-Built Drawings
01XXX Project Record Documents
01XXX Temporary Utilities and Controls
01XXX Support Facilities
01XXX Demobilization and Project Close Out
01XXX Operation and Maintenance

DIVISION 2 - SITE WORK

02050 Demolition
02110 Clearing and Grubbing
02210 Grading
02222 Excavation, Trenching, and Backfilling for Utilities Systems
02271 Waste Containment Geomembrane
02272 Separation/Filtration Geotextile
02273 Geonet
02287 Bioremediation Using Landfarming Systems
02442 Geosynthetic Clay Liner
02443 Low Permeability Clay Layer
02671 Ground Water Monitoring Wells

02720 Storm Drainage System
02730 Sanitary Sewers
02831 Chain-Link Fence
02XXX Well Abandonment
02XXX Hazardous Material Excavation and Handling
02XXX Excavation and Random Fill for Landfarm Liner Systems
02XXX Test Fill Sections
02XXX Leachate Collection System
02XXX Sand/Gravel Drainage Layer
02XXX Geogrid Reinforcement Material
02XXX Vadose Zone Monitoring Probes
02XXX Drainage Structure
02XXX Temporary Erosion and Sediment Controls
02XXX Permanent Surface Water Controls
02XXX Decontamination Facility
02XXX Roadways and Parking Areas
02XXX Water Lines
02XXX Contaminated Liquids Removal
02XXX Site Maintenance
02XXX Demobilization and Project Close Out
02XXX Post-Construction Maintenance Activities

DIVISION 3 - CONCRETE

03100 Structural Concrete Formwork
03200 Concrete Reinforcement
03250 Expansion Joints, Contraction Joints, and Water Stops
03300 Concrete for Building Construction

DIVISION 5 - STEEL

05500 Miscellaneous Metal

DIVISION 11 - EQUIPMENT

11XXX Stormwater Transfer Pumps
11XXX Irrigation Pumps
11XXX Activated Carbon Adsorption System

DIVISION 13 - SPECIAL CONSTRUCTION EQUIPMENT

13XXX Nutrient Mixing/Feed System

DIVISION 15 - MECHANICAL

15XXX Valves, Pipe Hangers, and Supports
15XXX Thermal Insulation for Mechanical Systems
15XXX Process Piping and Appurtenances
15XXX Irrigation Piping and Appurtenances

DIVISION 16 - ELECTRICAL

16XXX Electrical Work